ICSBE 2023

The 14th International Conference on

Sustainable Built Environment -2023

The Kandy Conference

PROCEEDINGS BOOK

Volume I

Editors
Prof. Ranjith Dissanayake | Dr. Pradeep Gajanayake

Proceeding of the 14th International Conference on Sustainable Built Environment – (ICSBE) 2023

Vision

To drive innovative research for tomorrow's development

Mission

To meet colleagues, experts, and friends in the field and to exchange ideas and those about research development work, concepts and practical ideas in structural, Construction and management

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PREFACE

It is with great pleasure that we present the proceedings of the 14th International Conference on Sustainable Built Environment (ICSBE) 2023. This is the fourteenth consecutively organized conference following a series of international conferences since 2010, keeping its tradition of adhering to engineering excellence. Taking a step forward from the last thirteen events, the coverage of specialty areas in this conference has been diversified. This book contains the abstracts of research work from many different sub-specialties. We expect that all these abstracts will be presented at parallel sessions from 16th to 17th December 2023. We would like to express our appreciation to all keynote speakers for their valuable contributions to the development of a sustainable world. We are also very grateful to the authors for contributing research papers of high quality. The abstracts in this proceeding book have been reviewed by a panel of academic and professional experts who have vast expertise in their respective fields. The enormous work carried out by these reviewers is gratefully appreciated as well. We are also pleased to acknowledge the advice and assistance provided by the members of the local and international advisory committee and members of the co-chairs committee along with many others who volunteered to assist to make this very significant event a success. Furthermore, we acknowledge the financial sponsorship provided by many organizations that have been extremely supportive of the success of this international conference. It is the earnest wish of the editors that this proceeding book would be used by the research community and practicing engineers/scientists who are directly or indirectly involved in studies related to sustainable built environments.

Editors
Prof. Ranjith Dissanayake
Dr. Pradeep Gajanayake

The 14th International Conference on Sustainable Built Environment (ICSBE) 2023
15th to 17th December 2023, Kandy, Sri Lanka

A MESSAGE FROM THE VICE-CHANCELLOR, UNIVERSITY OF PERADENIYA

I am delighted to share a message marking the 14th International Conference on Sustainable Built Environment (ICSBE) 2023.

I commend the Conference for maintaining consistently high academic standards throughout its history. Over the past 14 years, it has provided an exceptional platform for engineers, scientists, and researchers to showcase advancements in research and development, as well as the practical application of new tools and technologies.

In line with its established legacy, the Conference is expanding its focus by embracing new areas, particularly technical and industrial collaborations. The technical sessions of the Conference, centered around the theme "Building Sustainable Nations," directly align with the university's current developmental plans. The University has initiated an ambitious plan aiming for significant advancements in all aspects by its centenary year in 2042. Central to these developmental plans is our dedication to sustainability, aligning with the specific goals outlined by the United Nations. I am confident that participants from the university will utilize the insights from the conference to refine and adapt our developmental strategies accordingly.

I extend my heartfelt congratulations to the organizing committee of ICSBE – 2023 and convey my sincere wishes for a successful, impactful, and inspiring conference.

Thank you.

Prof. M. D. Lamawansa
Vice Chancellor
University of Peradeniya

MESSAGE FROM THE CONFERENCE CO-CHAIRS

It is a pleasure for us to welcome all the participants to the 14th International Conference on Sustainable Built Environment (ICSBE) 2023 in Kandy, Sri Lanka. We, the co-chairs would gratefully like to mention the previous successful conference, which was held for thirteen consecutive years in Kandy, Sri Lanka. The theme selected for the conference Sustainable Built Environment is extremely relevant to today's world. With the vision of promoting innovative and sustainable research for tomorrow's development. We organize this conference as a meeting place of talents, knowledge, and dedication. Therefore, we trust that the conference will produce great ideas from a variety of research and exchange the knowledge of experts, colleagues, and friends who are working for the world's sustainable development. The conference focuses on the different sub-topics in the sustainable built environment: such as sustainable construction, sustainable infrastructure development & planning, urban green infrastructure & planning, sustainable cities and villages, waste & wastewater management for enhanced sustainability, advanced water & wastewater technology, rainwater harvesting, water conservation, solar energy, bio-energy, wind, and hydro-power energy, alternative clean energy, green advanced computations & communication, green energy economics, policy, financing & business practice, sustainable materials, material flows & industrial ecology, high-performance concrete, remove, recycle, repair of materials, building automation, indoor environmental quality, indoor plants, impacts of climate change, climate change & reducing greenhouse emissions, carbon footprint, impacts of sustainable bio-fuel, social impact & human behavior, climate risk management & mitigation, global climate model and landscaping. The best-selected papers will be published in Springer Nature as lecture notes in civil engineering. Other full papers (which are presented at the conference) are published as conference proceedings with ISSN number. The host city of the conference, Kandy, is a world heritage city famous for its unique architecture, culture, nature, beauty, and climate. We hope that you will enjoy your time in Kandy during the conference. We, the conference co-chairs express our sincere thanks to our guests, keynote speakers, authors, members of the international advisory committee, members of the editorial committee, sponsors, and many others who volunteered to assist to make this very significant event a success.

Prof. Ranjith Dissanayke
Prof. Priyan Mendis
Prof. Chintha Jayasinghe
Prof. Sudhira De Silva
Prof. Upul Attanayake
Prof. Chaminda Konthesingha
Prof. D. A. R. Dolage
Dr. Ajith Thambo
Dr. Balasubramaniam Janarathnan
Eng. Shiromal Fernando

The 14th International Conference on Sustainable Built Environment (ICSBE) 2023

MESSAGE FROM THE CHIEF GUEST

It is an honor and a privilege for me to pen this brief message, as the Chief Guest, on the occasion of the 14th International Conference of The Sustainable Built Environment, although this year’s theme is much more - on the multi-disciplinarity of sustainability.

First, I wish to congratulate the organizing committee ably led by Professor Ranjith Dissanayake for \`sustaining\` this \`Kandy Conference\` for over 14 years, which is no mean task by any measure. As an academic who has worked in all five continents as a clinician, teacher, and an executive Dean, I am well aware of the energy and the unremitting tenacity required for maintaining the vigor of such a conference series.

The theme of this year’s conference is multi-disciplinarity of sustainable development, and is built on the 17 sustainable Millennium Development Goals (SDGs) set in 2000, that were formally adopted by all 193 member states of the UN in September 2015, aiming at ending extreme poverty, protecting the planet and ensuring prosperity for all by 2030 (UN, 2015). The SDGs expanded the agenda to include issues such as climate change, sustainable consumption, but also quality education requiring all countries to take action including those with high levels of development.

The goal of education for sustainable development (UN, 2015, p. 21) entails that \` that all learners acquire the knowledge and skills needed to promote sustainable development, including, among others, education for sustainable development and sustainable lifestyles, human rights, promotion of a culture of peace and non-violence, global citizenship and appreciation of cultural diversity and its contribution to sustainable development.

I am proud to say as a Sri Lankan we have embraced this ethos of quality education for a very long period and what’s more with virtually free provision of quality education to all, despite being a developing nation, still facing many hurdles. This is exemplified by our 17 universities and the global diaspora of graduates in varying professions. Incidentally I hope many of you who are here today will have the opportunity to visit one of the most beautiful campuses in the world, a few miles away – our University.of Peradeniya Campus, built in 1942, along the lines of Cambridge University, UK, and adorned by the undulating Mahaweli river.

Although Sir Lanka and many other jurisdictions have some way to go before achieving the foregoing erudite goals \`of education for sustainable development\` conferences such as these help nurture the ethos and popularise these goals, particularly when held under the auspices of a tertiary education institute.

In closing this short message, I wish you all a wonderful and a productive conference with many networking opportunities, whilst at the same time enjoying the breath-taking vistas and cuisine Sri Lanka has to offer.

Sincerely,

Lakshman Samaranayake
Professor Emeritus and Immediate-Past Dean, Faculty of Dentistry
University of Hong Kong, Hong Kong

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DEVELOPING A MATHEMATICAL MODEL AND MOBILE APP FOR GREENHOUSE MONITORING AND CONTROL USING SENSOR INTEGRATION

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Abstract: The exact regulation and monitoring of environmental factors like air quality, soil moisture, and light intensity are necessary for achieving optimal plant growth. These requirements are frequently not met by conventional agricultural techniques which results in yields that are less than ideal. Contrarily, greenhouse farming provides a solution by building managed habitats specifically designed for particular crops. However, even farming in a greenhouse presents difficulties because ongoing manual inspection takes time and is prone to mistakes. By integrating sensor integration, mathematical modeling, and a mobile application for greenhouse monitoring and control, this study offers an all-encompassing solution. To solve these issues, a prototype system is created. Real-time data on essential parameters are gathered by seamlessly integrating multiple sensors throughout the greenhouse. The system's intuitive smartphone application is its brains. Farmers now have immediate access to environmental data and trends for the greenhouse thanks to this app. Adaptive weighted sensor data fusion is an innovative idea in contemporary agriculture. This method maximizes the accuracy of data integration by dynamically updating the relevance of sensor inputs based on altering environmental conditions. By combining the most pertinent data from multiple sensors, including temperature, humidity, and light intensity, a thorough and up-to-the-minute picture of the agricultural environment is created. This adaptive weighted sensor data fusion technology, when combined with mathematical models, provides farmers with precise insights and real-time modifications, encouraging improved yields, resource efficiency, and sustainable farming practices. A revolutionary method of greenhouse farming is provided by the combination of sensors, mathematical modeling, and a mobile application. Precision monitoring and control are made possible by this cutting-edge system, which ultimately improves crop growth and yield. This study advances the development of sustainable and effective farming techniques by utilizing technology to harmonize agricultural operations.

Keywords: Sensor integration; Greenhouse monitoring and controlling; Mathematical Model; Regression; Mobile application

1. Introduction

The greenhouse is an enclosed structure built to create an optimal environment for plants to grow. It is usually made of glass or plastic and is designed to trap heat, allowing for longer growing seasons and protecting plants from extreme weather conditions (Hassan, 2015). ") (Hoque, 2020). Greenhouses can be used for a variety of purposes, including commercial agriculture, research, and hobby gardening. They can be used to grow a wide range of plants, including vegetables, fruits, and ornamental plants. They can also be used to create a microclimate, which can be ideal for growing plants that would not normally be able to survive in the local climate (Hoque, 2020) (Redmond, 2020). Overall, greenhouses are a valuable tool for farmers, researchers, and hobby gardeners. Greenhouse monitoring and controlling using sensor integration involves the integration of multiple sensors to gather data about the environment within the greenhouse (Singh, 2018). This data is then analyzed and used to control various aspects of the greenhouse environment, such as temperature, relative humidity, light levels, soil moisture, and air quality (Goldammer, 2019). The sensors used in sensor integration for greenhouse monitoring and controlling may include temperature sensors, relative humidity sensors, light sensors, gas sensors, and soil moisture sensors. These sensors are typically connected to a central control system, which can be programmed to automatically adjust the greenhouse environment based on the data it receives (Gaikwad, 2016).

2. Literature Review

Sensors are an essential component of greenhouse monitoring systems, providing data on various environmental factors such as temperature, relative humidity, light, and soil moisture. (Sujin, 2021) and (Xia, 2022) have focused on the use of below mentioned different types of sensors for greenhouse monitoring, Temperature sensors: DHT22 temperature sensors, Relative humidity sensors: The same DHT22 sensors, Light sensors: The use of BHT1750 sensors, Soil moisture sensor - Capacitive soil moisture sensors, Air quality sensors: By using an MQ-135 gas sensor in a greenhouse, make sure that the air is healthy for plant (Hassan, 2015). ") (Goldammer, 2019).

Automation systems are used to control various environmental factors in the greenhouse, such as temperature, relative humidity, light, and irrigation. The mentioned two types of research (Goldammer, 2019) (Gaikwad, 2016) have focused on the use of different types of control methods for greenhouse control. An automatic fan for a greenhouse system is a device that helps regulate the temperature and airflow within a greenhouse. A water pump can be used to control the water level of the greenhouse (Choi, 2019). A mathematical model for greenhouse monitoring and control can be developed using a variety of techniques, such as physics-based modeling, and model predictive control (Haisong, 2017) (Kozlovskaya, 2022) These equations can be used to predict the temperature and relative humidity inside the greenhouse, as well as the energy consumption of the heating and cooling systems (Unninayar, n.d.).

3. Methodology

3.1. Simulation of the Approach

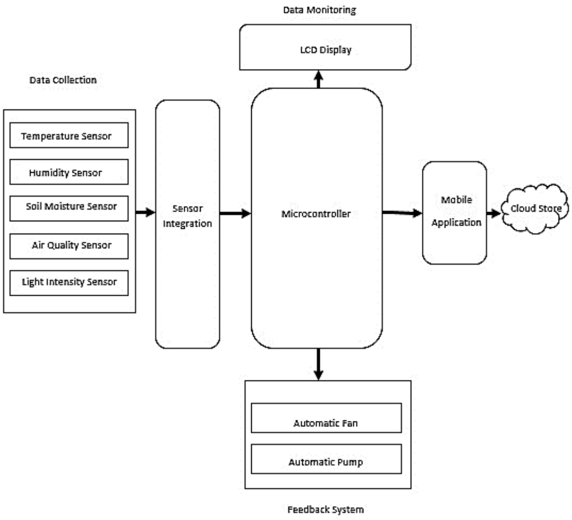


Figure 1: Overall Architecture.

Figure 1 depicts the block diagram of the implemented approach. The above-mentioned parameters should be changed in order to create a successful greenhouse system and allow diverse plants to flourish to their full potential. Four separate sensors, including a temperature sensor, a light sensor, a relative humidity sensor, and a soil moisture sensor, have been employed in this research to continuously gather data on these four crucial aspects. To track and manage greenhouse data by smartphone from anywhere in the world at any time, an Android app has been created. Arduino IDE is used to create the program. Once the program is successfully built in the IDE Arduino will load the application. Before the set-up installation, the Arduino code was simulated using Proteus to find the bugs and to understand the correct working procedure of the system for the data collection. The fan starts rotating when it exceeds 27 ^{0}C temperature and the pump starts thumping when the relative humidity level is less than 30% Fig 2. Shown the PROTEUS simulation.

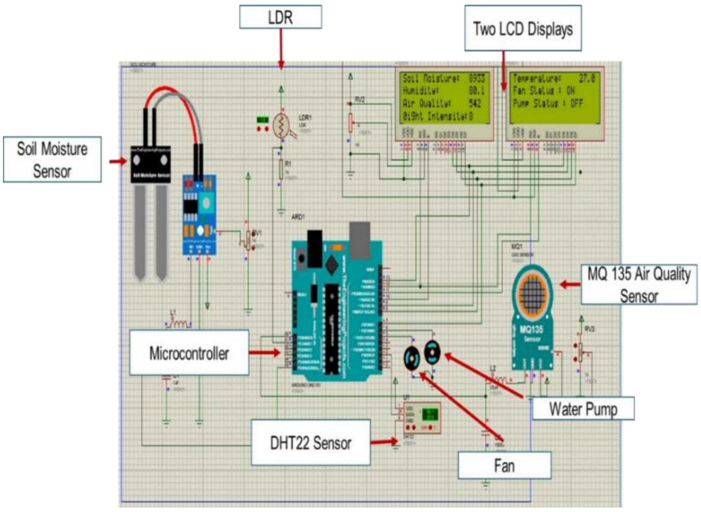


Figure 2: Proteus Simulation.

3.2. Real-World Implementation

Three set-ups have been placed in three different locations Kelaniya, Kandy, and Padukke. The 24V dc fan was powered by using a 24v power supply and it was connected to the micro-controller through a relay to protect the system, the pump was connected through a relay as well as the fan. Every other sensor mentioned above is connected to the micro-controller using jumpers and other components as resistors. Similarly, the data were gathered three times daily, in the morning, day, and night. Figure 3 shows three types of prototypes of the proposed automated greenhouse system to Kelanyai, Kandy, and Padukke.

Figure 3: Experimental Set-ups.

3.3. Android Application Development

The developed Android app was made using MIT App Inventor, The application has several pages as below.

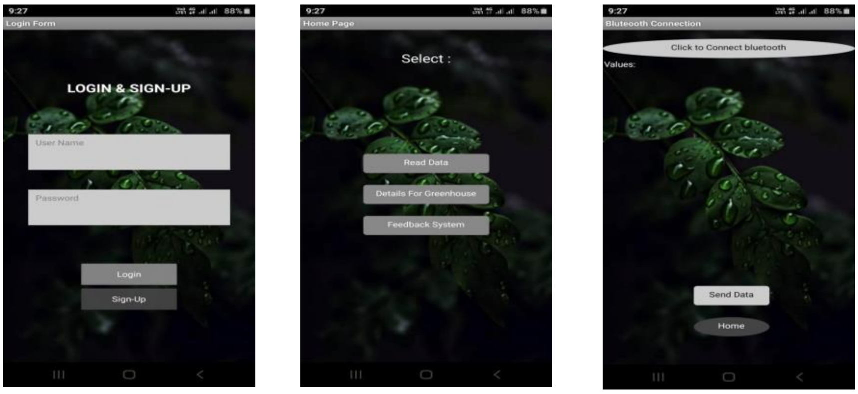


Figure 4: Login/Selection/Reading pages.

Figure 4 represents the Login / Sign up page for the app and the option list for the selections. First option for the real time data monitoring and the second option for the details of the greenhouse that farmer should know when green housing while third option is for the feedback system that can control the fan and the water pump installed in the approach as in Figure 5. This data can be collected from sensors and sent to Firebase in real-time data and then be displayed in the mobile app for monitoring and controlling the greenhouse remotely. Additionally, the app can use Firebase's real-time functionality to trigger alerts or automatically control elements in the greenhouse such as fans, water pumps, and heating systems based on the stored data. Figure 10 represents the saved data to the Firebase.

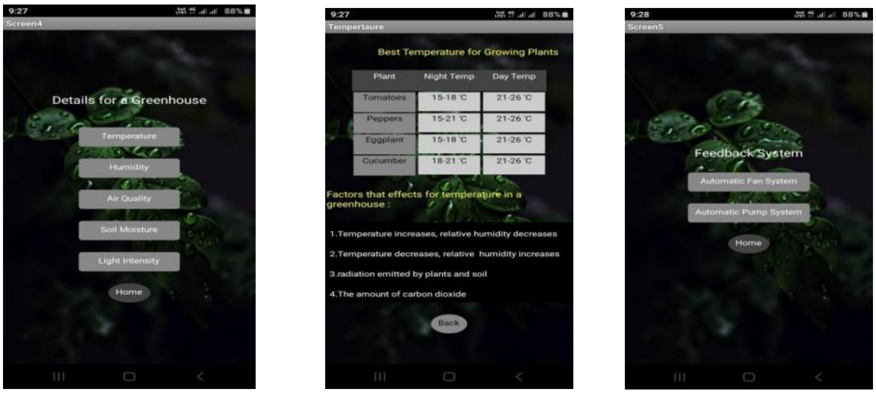


Figure 5: Details/Feedback System pages.

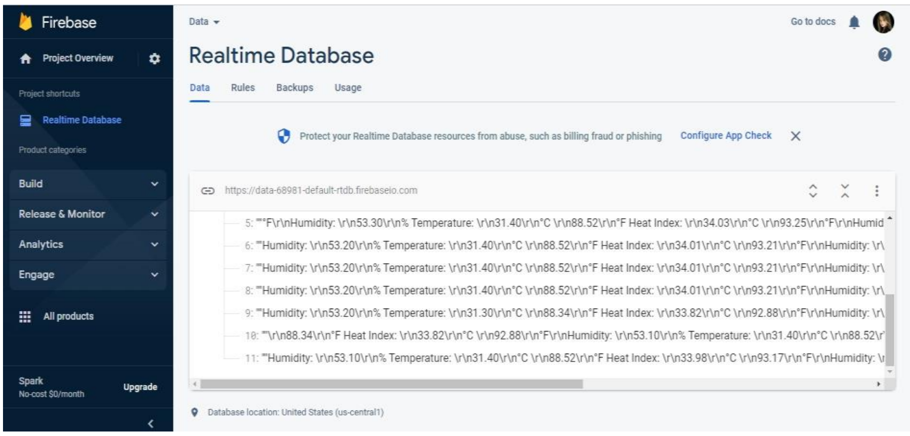


Figure 6: Firebase Real time Data Store.

3.4. Experiments

3.4.1. Under Normal Conditions

This setup, shown in Figure 7, was created to collect data, which were collected three times daily—morning, noon, and night—for a period of three consecutive days for the analysis and to develop the mathematical model.

Figure 7: Experiment under normal condition.

3.4.2. Humidity, Soil Moisture, Air Quality as functions of Temperature

This configuration, Figure 8, was designed to gather data when other parameters, such as soil moisture, humidity, light intensity, and air quality, are affected by temperature changes. Here light bulbs and a heater were used to increase the temperature.

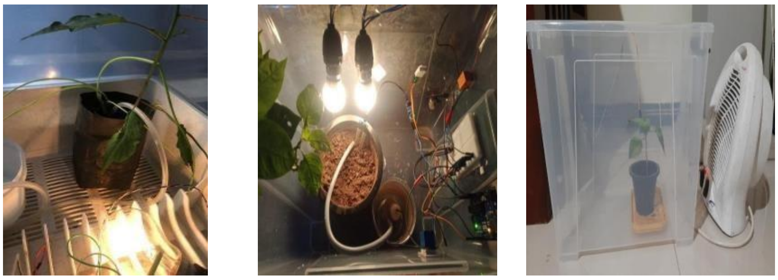


Figure 8: Experiment under control of temperature.

3.4.3. Humidity, Temperature, and Air Quality as Functions of Soil Moisture

This configuration, Figure 9 was created to gather data in situations where changes in soil water content affect other parameters such as temperature, humidity, light intensity, and air quality.

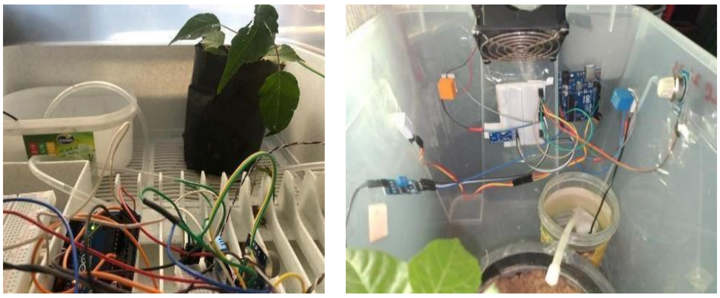


Figure 9: Experiment under control of soil moisture.

4. Results and discussion

The data collected from the greenhouse prototypes were analyzed using R studio for the regression. The analysis considers the data collected and the plant's condition. Regression analysis was performed using R studio on data collected by dividing into two stages humidity as a function of temperature, Soil moisture as a function of temperature.

4.1. Humidity as a Function of "Temperature"

Table 01: Summary of the data set

	Min	1Q	Median	Mean	3Q	Max
Temp..Inside	25.2	25.3	25.4	25.42	25.57	25.6
Humidity	77.7	77.8	78	78.01	78.2	78.3

Table 02: Model Results

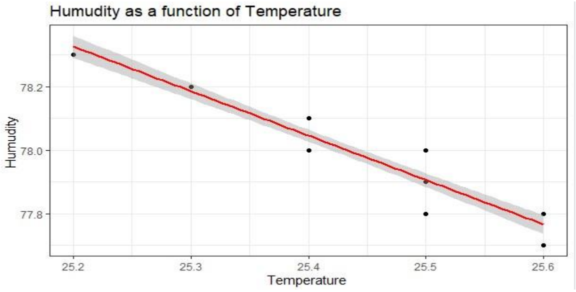
Min	1Q	Median	Mean	3Q	Max
0.105975	0.02607	0.003992	0.034058	0.094025	0.100584

	Estimated Std.	Error T.	Pr(>|t|)
Intercept	113.61429	1.63759	69.36<2e-16
Temp.inside	-1.40033	0.06443	-21.73
Signif. Codes	0	0.001	0.01
Residual st	0.02047 on 28 degrees		
Multiple R-squared	0.944		
F statistic	472.4 on 28DF. P-value <2.2e-16		

Coefficient Model:

	2.50%	97.50%
Intercept	110.259106	116.969466
Temp.Inside	-1.52296	-1.268356

4.1.1. Regression Line to the Graph



Graph 01: Regression Line.

4.2. Soil Moisture as a function of "Temperature"

Table 03. Summary of the data set

	Min	1Q	Median	Mean	3Q	Max
Temp..Inside	25.2	25.3	25.4	25.42	25.57	25.6
Soil Moisture	4.3	4.3	4.3	4.347	4.4	4.4

Table 04. Model Results

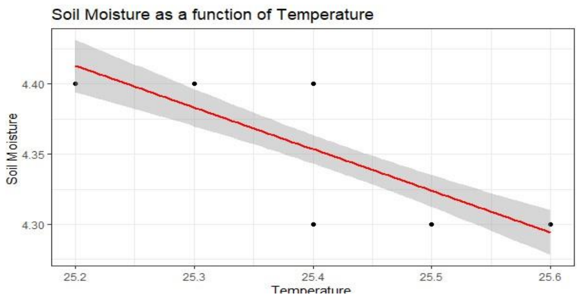
	Estimated Std.	Error T.	Pr(>|t|)
Intercept	11.91429	0.87372	13.636
Temp.inside	-0.29766	0.03437	-0.662
Signif. Codes	0	0.001	0.01
Residual st	0.026 on 28 de-grees		
Multiple R-squared	0.7282		
F statistic	75.02 on 1 and 28 DF. P-value 2.076e		

Min	1Q	Median	Mean	3Q	Max
0.053612	0.021171	0.005921	0.016621	0.046388	0.062583

Coefficient Model:

	2.50%	97.50%
Intercept	10.1245583	13.7040132
Temp.Inside	-0.3680602	-0.2272684

4.2.1. Regression Line to the Graph



Graph 02. Regression Line.

4.3. The Data Fusion Algorithm

The data were processed by using the fusion algorithm. According to the data processing process suggested the collected data were first preprocessed to eliminate any outliers. The outliers are measurement values that exceed the normal measurement error range. Outliers occur due to interference and environmental factors. The test results, test conclusions, and results are interfered with by outliers in the collected data. The Grubs criterion has been used to eliminate the outliers.

Temperature

G = 1.60127, U = 0.85795, P-value = 1

Alternative hypothesis: The lowest value 29.8 is an outlier

Humidity

G = 1.56575, U = 0.86418, P-value = 1

Alternative hypothesis: Highest value 84is an outlier

Soil Moisture

G = 6.6283717, U = 0.0019633, P-value = 2.2e-16

Alternative hypothesis: Highest value 84 is an outlier

Air Quality

G = 1.67302, U = 0.87852, P-value = 1

Alternative hypothesis: Lowest value 139 is an outlier

Then the following weighting factor calculation was used to calculate the weighting factors of the sensors.

$$W_p^* = \frac{1}{\sigma_p^2 \sum_{p=1}^{n} \frac{1}{\sigma_p^2}} \qquad (2)$$

The following results show the results obtained using SPSS software after the computation calculation of the weighted factor equation using the variance.

Table 05: Weighted Factors

Sensors	Weighted Factors
Temperature	0.44
Humidity	0.15
Soil Moisture	0.23
Air Quality	0.17
Light Intensity	0.02

4.3.1. Discussion on Regression Models

The ratio between the weight of moisture and the total moisture capacity of a unit volume of air is given by relative humidity. When considering previous approaches in determining the relationship between the relative humidity and the temperature it shows an inversely proportional relationship where the relative humidity is dependent on the temperature. When comparing the plotted graphs and the functions generated, the results of the regression analysis of the humidity as a function of humidity satisfy the conditions and relationships obtained from previous approaches and literature. The results are analyzed because a microclimate is maintained inside the greenhouse which does not get interfered with by the exterior environmental conditions.

Soil moisture is the amount of moisture and water content in a sample of soil. Previous literature on the relationship between temperature and soil moisture states that the rise of temperature increases the evaporation rate of the soil. Hence the previous literature explains the relationship between soil moisture and temperature as inversely proportional. This relationship is satisfied by the results obtained and the graphs plotted from this approach.

Regression is a statistical tool used to identify the variables that have an impact. The variables can be divided into dependent and independent. The dependent variables are the variables that are being predicted and the independent variables have an impact on the dependent variable. Linear regression establishes the linear relationship between two variables based on a line of best fit. A regression model is able to show whether changes observed in the dependent variable are associated with changes in one or more of the explanatory variables. Linear regression models often use a least-squares approach to determine the line of best fit. Nonlinear regression is a form of regression analysis in which data is fit to a model and then expressed as a mathematical function. A mathematical model is an abstract model that uses calculations and equations to describe the behavior of a system. In this approach, a linear regression model has been used to identify the association between the parameters inside a greenhouse.

The multiple linear regression model used in this approach shows both the magnitude of such an association and also determines its statistical significance. Data collected from the Temperature and Humidity Sensors has been modeled considering humidity(y) as the dependent variable and temperature (x) as the independent variable.

Table 07: Equations that Obtained

Equation 1	Kandy	y=4.687-0.06x
Equation 2	Padukka	y=6.6434-0.12x
Equation 3	Kelaniya	y=3.1799-0.06x

A linear model is constructed by naming temperature as the dependent variable and humidity, soil moisture, air quality, and light intensity as the independent variables. The following equations represent the linear model equation between the dependent and independent variables. The following equation shows the common format of the equation.

Table 08: Common Equations

	Temperature(y)= Intercept + Humidity (x1)+Soil Moisture(x2)+Air Quality(x3)+Light Intensity(x4)
Kandy	y=53.55205-0.17666xa-0.95873x2-0.17854x3
Pad-ukke	y=5.86010-0.2143x1+08264x2-0.1765x3
Ke-laniya	y=49.8946-0.154x1-0.5115x2-0.19564x3

In this study t-test, correlation coefficient, and coefficient of determination are selected to evaluate the relationship between variables/attributes and the forecast accuracy of the proposed regression model. The t-test can be used to test the significance of the slope and it can be obtained by dividing the coefficient by the standard error. A positive correlation signifies that both variables are moving in the same direction and a negative correlation signifies the fact the two variables are moving in opposite directions. The coefficient of determination (R$^{2)}$ indicates the strength of the model. Positive R^2 indicates that the predictions match the observations perfectly and a 0 indicates that the predictions are as good as random guesses around the mean of the observed values and negative R^2 indicates that the predictions are worse than random. Since the three equations are similar the first equation will be discussed here. The first equation can be analyzed in the following table. Even though the common formula has four coefficients it could be observed that in the mathematical model, only three coefficients are present. The light intensity coefficient has a nearly equal to zero value hence it is neglected in the equations.

Table 09: Summary for data

	Estimate	**Std.Error**	**T-Value**	**Pr(>|t|)**
Intercept	53.55205	10.67337	5.017	3.21E-05
Humidity x_1	-0.17666	0.15536	-1.137	0.266
Soil Moisture x_2	-0.95837	0.91161	-1.051	0.303
Air Quality x_3	-0.17854	0.03625	-4.925	4.09E-05
Light Intensity x_4	NA	NA	NA	NA
Residual Standard Error	0.1226 on 26 degrees of freedom			
Multiple R-squared(R$^{2)}$	0.914			
Adjusted R-squared	0.9041			
p-value	5.64E-14			

The coefficients of the mathematical models can be summarized in the following table.

Table 10: Obtained Models

	Humidity x_1	Soil Moisture x2	Air Quality x3	Light Intensity x4
Kandy	-0.17666	-0.95837	-0.17854	NA
Padukka	-0.2143	-0.8264	-0.1765	0.004
Kelaniya	-0.1548	-0.5115	-0.19564	NA

5. Conclusions and Future Works

The developed, low-cost greenhouse model can be used to monitor and regulate a greenhouse's temperature, light intensity, humidity, air quality, and soil moisture, which will increase farming productivity, particularly in nations like rural where there is a high risk of insect infestation, a harsh climate, and rising food demand due to the shrinking amount of arable land. Since the model is automated, it does not require human intervention to smoothly manage the plant. A mobile application has been incorporated into this model to examine the data. The results obtained from the sensor integration after data collection were sent to the LCD and Android application through microcontroller and Bluetooth. A message can be sent to a mobile device using the Bluetooth module when a parameter exceeds a threshold value. From the regression analysis performed on temperature and humidity sensors, a clear relationship between the humidity and the temperature could be observed hence an inversely proportional relationship exists between the temperature and humidity. The future work includes the development of the sensor fusion algorithm and applying wireless sensor fusion to greenhouse monitoring. The system developed in this project can be used as a model for future greenhouse monitoring and control systems and it could be further developed to be more sophisticated and efficient.

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ENHANCING THE FLOOD MODELING ACCURACY UNDER VARYING SPATIAL SCALES FINER RESOLUTION WEATHER DATA

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Abstract: Global Climate change is leading to extreme weather conditions, and they occur more frequently. Floods are among the major natural disasters that cause loss of lives and economic damage worldwide. Therefore, reliable flood forecasting and warning systems are required to alert the public and governing authorities as early as possible. In most countries, river basins are sparsely gauged, and lack accurate and adequate rainfall, soil moisture, and discharge measurements. This contributes to higher uncertainty in predicting hydrological responses in such areas. Considering the recent severe floods and water management issues of the City of Wangaratta in Australia, the Ovens River basin (>6000 km2) in Australia has been modeled using GR4H – hydrologic model with lag and route channel routing. A moderate density of weather stations with hourly discharge, precipitation, and PET data (2007-2017) was used in a semi-distributed catchment model with 53 sub-areas. Data sparse situation was simulated with only five weather stations for the entire basin. Model results revealed 0.77 NSE for calibration for 7 years, and 0.81 NSE for validation for 4 years for the semi-distributed model. Data sparse condition simulation performed well with 0.84 NSE promising the model prediction capability under limited weather data. Most importantly, X1 to X4 four parameters of the GR4H model do not show significant variation comparing densely gauged catchment and sparsely gauged catchment. This hydrological modeling process is critical in data-sparse areas but not limited to ungauged catchments.

Keywords: GR4H; Flood; Modelling; Forecasting; Ungauged

1. Introduction

Flood modeling became popular with the development of computational power. Also, hydrological, and hydraulic models are now integrated to represent the dynamics of hydrometeorological events (Chen, et al., 2021). These models include one-dimensional, two-dimensional, and three-dimensional methods that use physical laws and equations to describe the flood movement along the flood plain and the river channel. However, data scarcity and data resolution compromise the model's predictability. In this regard finer resolution remotely sensed data with bias correction has been widely used in literature (Chao, et al., 2022); (Silvestro, et al., 2015); (Le, et al., 2023); (Lee, et al., 2023). Generally, coarser resolution sparsely distributed hydrometeorological data are available in most river basins. In such a situation, when the number of model parameters increases, it is difficult to differentiate the physical meaning of each parameter during the calibration process as some observations will not be captured by the model due to coarser resolution input data. This issue has been widely identified as stream responses concerning rainfall events have not been represented by the model.

In some cases, finer temporal resolution data can be there with thinner spatial distribution. Modeling this situation with finer model computation time steps will make sure no details will be lost in between the computation time steps. GR4J, IHACRES, MISD, and GR4H are a few examples of physically based or white-box models used in rainfall-runoff modeling (Nayak, et al., 2021); (Mohammadi, et al., 2022); (Tahroudi, et al., 2023). They always provide insights into the physics of the problem and easy to understand or reverse engineering. Another type is machine learning or the black-box models like artificial neural networks (ANN), support vector machine (SVM), and adaptive neuro-fuzzy inference system (ANFIS) where the black-box models have robust computation ability (Rathnayake, et al., 2023); (Mohammadi, 2021); (Jehanzaib, et al., 2022). GR4J parsimonious model has been used in several studies with daily resolution data as it has been proven to be more effective than complex models like TOPMODEL (Beven, et al., 2021), IHACRES (Mohammadi, et al., 2022); (Tian, et al., 2013); (Kunnath-Poovakka & Eldho, 2019); (Zeng, et al., 2019). GR4H is a variant of GR4J for sub-daily time-step applications. (Benkaci, 2023); (Basri, et al., 2019).

The objective of this study is to generate a robust model and simulate the data scarcity condition to evaluate the model's performance. In this study we aim to improve the accuracy of hydrological simulation of GR4H model in coarser spatial resolution but with finer temporal resolution of weather data. Model output has improved by the lag & route channel routing to minimize the hydrograph recession errors.

2. Materials and methods

2.1 Study Area

The Ovens basin covers 0.7 percent of the Murray Darlin basin (MDB) and contributes approximately 6 percent of the total runoff of the MDB (CSIRO, 2008). Catchment rainfall varies dramatically across the basin due to the broad range from alpines (1600mm) to lower floodplains (550mm). The average rainfall is 1196 mm/ year, and the average annual streamflow is 1775 GL at Peechelba (Murray–Darling Basin Authority, 2023). The Ovens basin at Wangaratta 6239.32 km^2 comprises three main rivers named Ovens River, Kings River, and Buffalo River (Figure 1). The Ovens River rises in the Victorian Alps and flows 190 km to join the river Murray near Lake Mulwala. The river segment from Wangaratta to Lake Mulwala has been considered as an asset of national importance considering the environmental sensitivity and the river features (CSIRO, 2008). The Ovens River is the least regulated in the MDB having only two reservoirs Lake Buffalo (24 GL) in Buffalo River and Lake William Hovell (14 GL) in King River (Figure 2). Water management of the Ovens basin is extremely important as the city of Wangaratta contributes to the national economy through agriculture and acting as an industrial manufacturing hub. The year 1993 was the recorded highest flood in Wangaratta causing severe economic loss. There were another three flood events in year 2010, 2016, & 2020.

Hume Dam in Murray River with 1417 GL capacity located upstream of the Ovens basin (Figure 2) plays a major role in flood controlling in lower MDB and maintaining downstream water security. However, release and the storage of the water from the Hume Dam is a critical decision with the climate change-induced extreme weather conditions. In this regard, the Ovens basin runoff contribution to the MDB estimation is vital to make accurate decisions. Also, the Oven basin has a significant number of intermittent gauging stations and updated weather records which can contribute to generating a robust hydrological model with reliable flood estimation. With an accurate runoff forecast, Hume Dam water release can be controlled with the highest efficiency. However, the accuracy compromises with the data resolution and the scarcity.

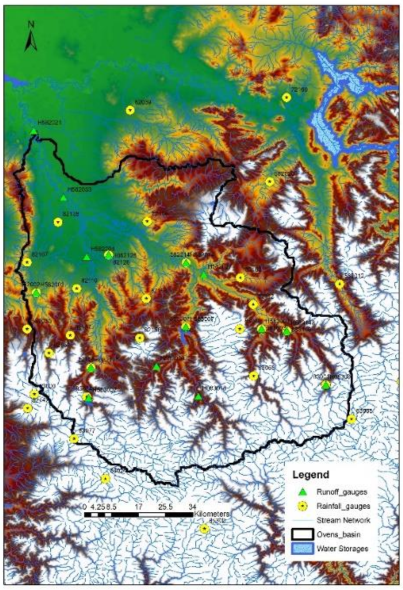

Figure 1: Ovens basin at Peechelba

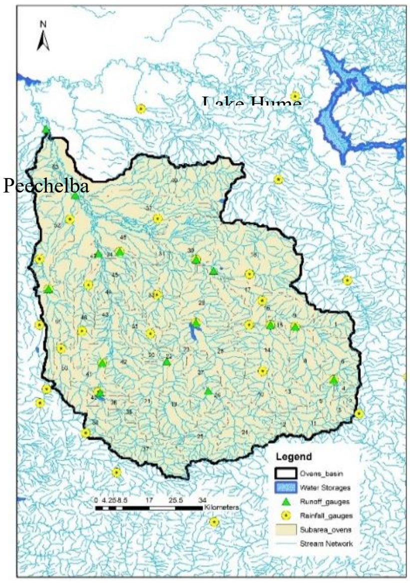

Figure 2: Stream network and the gauging stations of Ovens basin.

2.2 Data

Geographic data including surface network, surface cartography, surface catchments, & groundwater cartography were provided by the Geofabric National version 3.3.x from the Bureau of Meteorology, Australia. One second SRTM-derived DEM was provided by Geoscience Australia (Gallant, et al., 2011). The surface network of Geofabric data was verified against the DEM flow directions using Arc GIS 10.8.2.

2.3 Gauge data

Gauge data including precipitation, potential evapotranspiration (PET), and streamflow data with a one-hour temporal resolution were provided by the Bureau of Meteorology, Australia for the 2007 to 2017 period. There were fifteen streamflow gauging stations and thirty-four rain gauge stations in the Ovens basin. Station rainfall records were interpolated into model sub-area centroids by the inverse distance weightage (IDW) method. Hourly resolution PET data was also interpolated in the same procedure. Precipitation and streamflow data were verified by comparing them with the data archives of the water measurement information system of the Department of Environment, Land, Water, and Planning (Department of Environment, Land, Water & Planning, 2023).

2.4 Model development

2.4.1 GR4H Model

The GR4J four-parameter model was developed by Perrin, et al., (2003) that relates runoff (Q) to rainfall (P) and evapotranspiration (E) using daily data. Streamflow data are used for model calibration and evaluation. Production storage (S) and routing storage (R) are used as the initial state variables of the model. The net precipitation (Pn) is calculated after removing the interception loss from P. Then the Pn is divided into infiltration (Ps) which convey to the production store with a maximum capacity of X1, and direct runoff (Pn-Ps). The percolation from the production store and direct runoff are added to produce the total runoff (Pr). 90% of Pr is routed by a unit hydrograph (UH1) with time base X4 and then routed through a non-linear routing store (R) of capacity X3. 10% of Pr is routed by a unit hydrograph (UH2) with a time base of 2X4. X2 represents the groundwater exchange coefficient, which is positive when water is imported, negative when water is exported, and zero for no exchange of flow.
The GR4H model is a variant of GR4J having the same model structure but working with hourly data (Basri, et al., 2019); (Ayzel & Heistermann, 2021); (Han, et al., 2019). The model parameters and the units as shown below.

GR4H X1 production store capacity [mm]
GR4H X2 groundwater exchange coefficient [mm/h]
GR4H X3 routing store capacity [mm]
GR4H X4 unit hydrograph time constant [h]

Figure 3 shows the schematic of the GR4H model. It was selected because it is simple and has relatively fewer parameters to optimize (Nayak, et al., 2021). Out of the 15 streamflow gauging stations, 12 stations were selected for model calibration. Starting from the headwater sub-catchments GR4H model was applied in the order of the node-link diagram shown in Figure 4. Model-generated runoff has routed through the reach with lag & route method.

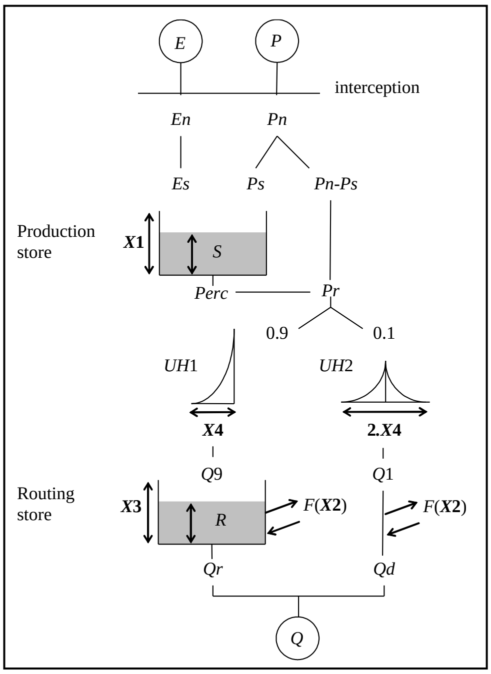

Figure 3: Schematic diagram of GR4H model (Perrin, et al., 2003).

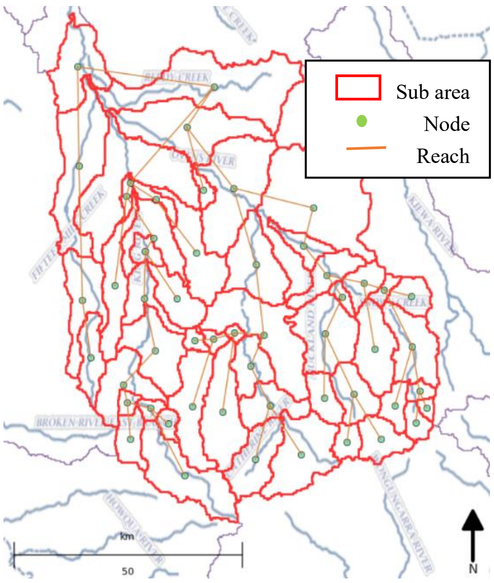

Figure 4: Node Link diagram of semi distributed model.

2.4.2 Lag and route method

Mass balance is given by equation (1), and equation (2) establishing a parameterised relationship between the stored volume and the outflow. Equation (3) provides the aggregated flow over the time step of duration **δ**.

$$\frac{dv}{dt} = q_1(t-\tau) - q_2(t) \quad (1)$$

$$q_2(t) = q^* \left(\frac{v}{\theta_1}\right)^{\theta_2} \quad (2)$$

$$Q_2 = \frac{1}{\delta}\int_0^{\delta} q_2(t)dt \quad (3)$$

V represents the stored water volume within a river reach. $\mathbf{q_1}$ and $\mathbf{q_2}$ are inflow and outflow. $\mathbf{q^*}$ is the reference flow. $\boldsymbol{\tau}$ is the lag parameter controlling the lag applied to the inflow. $\boldsymbol{\theta_1}$ and $\boldsymbol{\theta_2}$ are dimensionless constants.

$$Q_2 = \frac{v_0 - v_1}{\delta} \quad (4)$$

$$v_1 = \omega\left[1 - \left(1 - \frac{v_0}{\omega}\right)e^{(-I\delta\omega)}\right] \quad (5)$$

$$\omega = I\frac{\theta_1}{q^*} \quad (6)$$

$$I = q_1(t-\tau) \quad (7)$$

$$\tau = \alpha LU \quad (8)$$

$$\theta_1 = (1-\alpha)q^*LU \quad (9)$$

$\theta_2 = 1\ or$ (Linear storage or quadratic storage). **U** is the inverse of a velocity and $\boldsymbol{\alpha}$ is a shape parameter. **L** is the length of the river reach. Semi-distributed model computations were completed step by step up to the oven basin outlet at Wangaratta. GR4H X1 to X4 four parameters and U & α optimized to calibrate the model with GRG non-linear algorithm in solver.

2.4.3 Model Calibration and Verification

In the model calibration, the six parameters (X1, X2, X3, X4, U, α) were optimised to maximize an objective function that incorporates the Nash-Sutcliffe efficiency (NSE) of hourly runoff together with an estimation of Bias between observed and modelled runoff for seven years from 2007 to 2013. The year 2007 was allocated for the model warmup period and it was not considered for the NSE and Bias calculation. The resulting optimized model parameters are therefore identical for all the sub-areas within the gauged sub-catchment. Likewise for the twelve gauging stations above six parameters were optimized and observed the parameter variation. The parameter set obtained for the Ovens basin outlet gauging station (Wangaratta) was used to verify the model for the duration of four years from 2014 to 2017.

2.4.4 Data Sparse Situation Simulation

Data sparse situation was simulated with only five weather stations for the entire basin (Figure 5). IDW average precipitation and PET were considered for the model and assessed for the calibrated parameters of the semi-distributed model. For the comparison, the six parameters of the lumped model were re-optimized with the GRG non-linear algorithm in the Excel solver.

3 Results and Discussion

Figure 6 and Figure 7 compare the modeled and observed hourly runoff and the hydrographs for the selected six calibration sub-catchments. The calibration results are amongst the best having satisfactory NSE on average greater than 0.74. The summary of the NSE for twelve sub-catchments is shown in

Table 1. Figure 8 and Figure 9 show the modeled and observed hourly runoff and the hydrograph for the verification period.

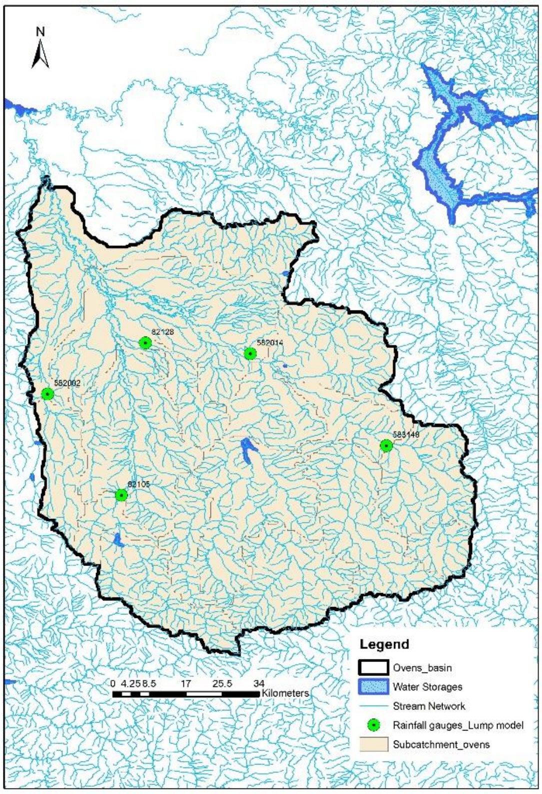

Figure 5: Data sparse situation representation with only five rain gauges.

Table 1: Optimized model parameter values summary and NSE values

Station ID	**Station Name**	**X1**	**X2**	**X3**	**X4**	**NSE**
H083001	Harrietville	955.1011	-2.89463	198.086	13.16018	**0.64**
H583148	Bright	1231.634	-3.59997	101.561	8.066365	**0.76**
H583003	Harris lane	933.3862	-1.97695	106.9486	7.753892	**0.75**
H583000	Matong North	330.8139	-5.14125	81.24894	17.60031	**0.71**
H083018	Abbeyard	645.7298	-4.3411	126.8413	10.70167	**0.81**
H583002	Lake WH	373.506	-0.66028	71.77508	9.822346	**0.62**
H583007	Lake Buffalo	512.0523	-11.4586	98.4089	16.36187	**0.65**
H582027	Myrtleford	1000.609	-2.38638	114.0856	13.45488	**0.85**
H582002	Greata South	523.8505	-1.4627	28.09489	8.00108	**0.8**
H582033	Wangaratta	668.4003	-1.66618	67.26751	42.4577	**0.78**
H582004	Docker Rd	339.2571	-1.67769	59.60462	20.46958	**0.73**
H582021	Peechelba	597.4241	-3.30155	139.9429	46.99994	**0.77**

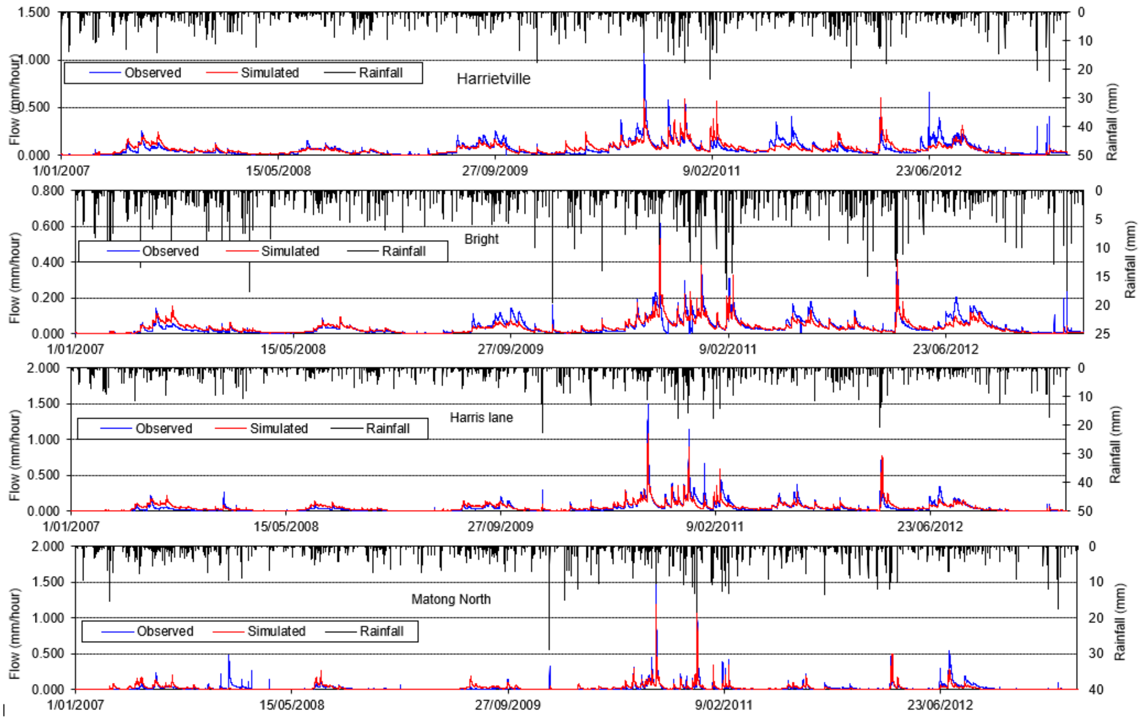

Figure 6: Observed and Simulated hydrographs for selected sub catchment models.

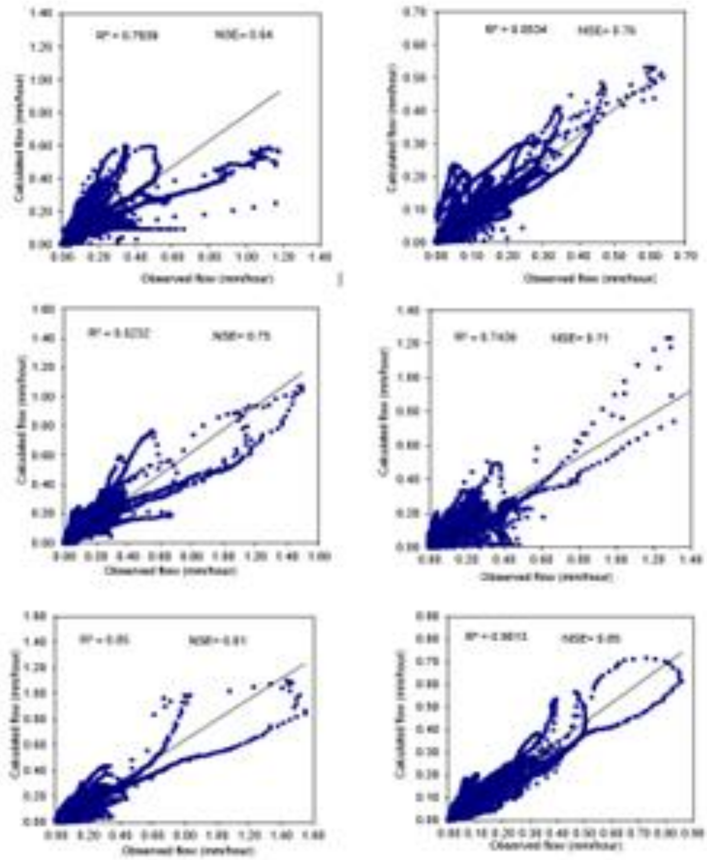

Figure 7: Observed and Simulated runoff of selected sub catchment models.

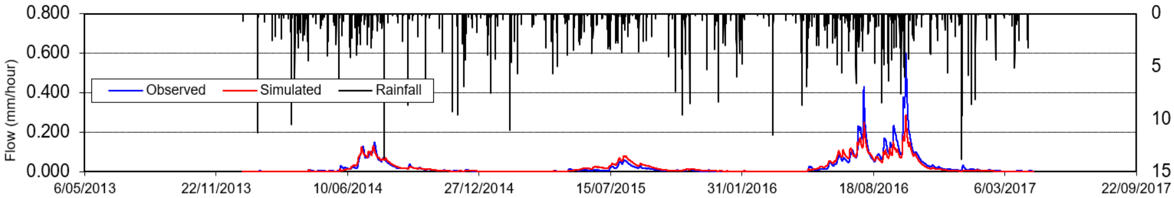

Figure 8: Observed and simulated hydrograph of Verification period.

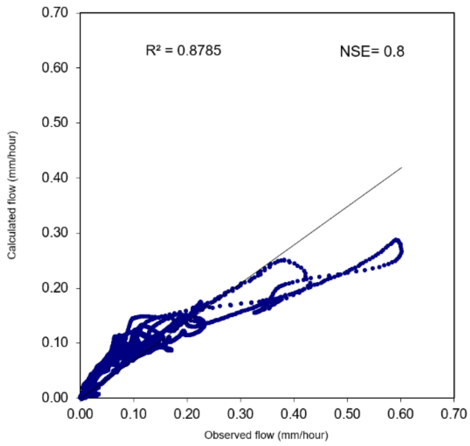

Figure 9: Observed and Simulated runoff of verification period.

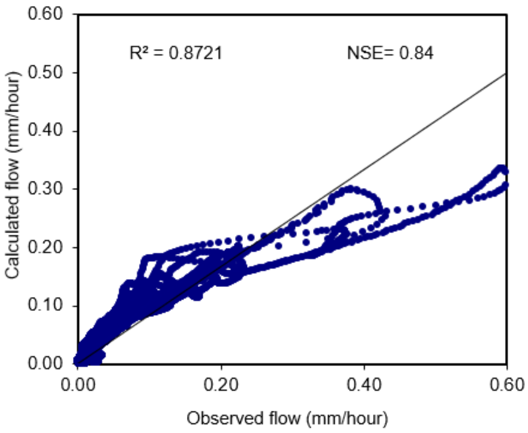

Figure 10: Lumped model simulated and observed flow for the verification period.

The lowest value of NSE was obtained for the Lake William Hovell and Lake Buffalo stations where the reservoir regulation affects the observed flow. The major peek of observed and simulated hydrograph comparison shows significant disagreement in both calibration and verification periods. However, further investigation confirms that the major peaks of the gauged streamflow data have been overestimated and the data archives of the water measurement information system of the Department of Environment, Land, Water & Planning (Department of Environment, Land, Water & Planning, 2023) confirm this variation. Therefore, the model predictions can be accepted with no doubts. Also, the model X2 parameter shows lesser negative values indicating insignificant disappearance of water maintaining the mass balance. Figure 10 shows the best performance of the lumped model with only 5 gauging station data having 0.84 NSE value. This is promising that the GR4H's capability in limited gauge or ungauged situations.

4 Conclusion

The performance of the GR4H parsimonious model with lag and route channel routing in data scares situations is well established in the Ovens basin. Data sparse situation was simulated with only five weather stations for the entire basin. Model results revealed 0.77 NSE for calibration for 7 years, and 0.81 NSE for validation for 4 years for the semi-distributed model. Data sparse condition simulation performed well with 0.84 NSE promising the model predictability under limited weather data. The model can be used to predict the runoff from the Ovens basin even for the forecasted precipitation and PET. The outcome of this study would help to manage the water resources downstream of MDB including the water security of Lake Hume. The hydrological modeling process followed by this study can be checked for similar data-sparse areas but not limited to ungauged catchments.

Acknowledgments

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TRANSFORMING HOUSING RETROFIT: THE POTENTIAL IMPACT OF ARTIFICIAL INTELLIGENCE

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Abstract: 80% of the housing stock by 2050 in the UK has already been built. Currently, the UK housing stock contributes 18% of the total UK emissions. Due to the legal requirement of the UK government to achieve net zero by 2050, the housing stock poses a considerable challenge to achieve this objective. Accordingly, reducing the energy demand of the housing stock through sustainable retrofit is a key priority. However, various reasons have been slowing down the progress of housing retrofit in the UK. Artificial intelligence [AI] has become a contemporary buzzword due to the emergence of GPT and its use in different industries. Considering the above, this study first sets out to identify how AI can establish improvements in current processes. Secondly, it identifies what areas can be best optimized with AI. A literature review was conducted to establish the existing retrofit processes and to understand the potential of AI. Thereafter, an empirical study was conducted using semi-structured interviews with software engineers involved in AI to find the potential of AI in housing retrofit. The findings of the study mainly benefit policymakers, homeowners, retrofit professionals, and construction companies. Considering the dire need to push housing retrofit forward to achieve Net Zero goals, this study can help develop ideas. However, this study will show only the possible directions for driving retrofit, not an exact solution. The literature suggests that the benefits of housing retrofit are for both the homeowners and the society. Although the benefits to the homeowners are set aside, it is not possible to ignore the sustainability purpose of retrofit as climate change is a documented reality. As the revolution of artificial intelligence is now a reality, the synergy of housing retrofit and AI is an important opportunity.

Keywords: Artificial intelligence; Energy efficiency; Housing retrofit; Sustainability

1. Introduction

The UK government is on a legally bound mission of net zero 2050. The UK needs to achieve net zero carbon emissions by 2050 (UK Government, 2019). 18% of these emissions are currently coming from the energy consumption of the housing stock (Passivhaus Trust, 2021). 80% of the houses by 2050 are already be built (CITB, 2021). The UK is currently reported to have nearly 30 million housing stock and 66 million people are living there (BRETrust, 2020). As these emissions of the housing stock mainly come from the energy consumption of the houses, reducing energy demand through retrofitting houses is a timely need (Parliament UK, 2021). Net zero is not possible to achieve only by energy decarbonization without reducing energy consumption (LETI, 2021).

According to BSI (2019), housing retrofit can be defined as making updates to houses in terms of improving energy efficiency, ventilation, or reducing emissions. However, the retrofit can take different forms such as energy retrofit (Ruparathna et al., 2017), seismic retrofit (Caterino et al., 2008), or structural retrofit (Dauda & Ajayi, 2022). In general, the benefits of housing retrofit are not all about energy or structure, it covers a broad range of benefits to the homeowner and the whole society. Energy efficiency, improved ventilation, improved comfort, improved health, property value increase, and increased durability are some of the examples (LETI, 2021; TheIET, 2020; Passivhaus Trust, 2021).

Artificial intelligence can be identified as the technology where computers behave like humans in general. Artificial intelligence covers a broad range of disciplines. It is mainly driven by technologies such as machine learning and deep learning (Google Cloud, 2023). Artificial intelligence uses computer science to analyze a massive amount of data to solve problems, which usually require human intervention (IBM, 2023). The founder of Facebook, Mark Zuckerberg says the future AI will be superintelligent. Further, he argues the main two problems with AI the security and access. However, he emphasizes that even with the current level of AI, there is a high level of value to unlock for people (Zuckerberg, 2023).

Housing retrofit is something that needs to be accelerated for the next three decades in the UK for net zero in 2050 (DBEIS, 2021). However, according to IEA (2021), the progress of housing retrofit is extremely poor. Without a significant turnaround in the way of driving retrofit, the trajectory of retrofit completion will not meet 2050. The UK government is also relying on innovations to expedite the journey to net zero 2050 (UK Government, 2021). Accordingly, the paper focuses on how to use artificial intelligence to drive housing retrofit.

2. Methodology

The existing knowledge is observed to be strong in the areas of artificial intelligence as well as in housing retrofit. However, the literature articles and even grey literature about using AI in housing retrofit are critically low. Considering the factors, it was decided to use an inductive approach for this paper. Further, considering the highly technical nature of these topics, a questionnaire survey is less likely to produce a meaningful outcome. Accordingly, interviews were selected as the data collection strategy. Qualitative data collection and analysis were used under the interpretivism philosophy, by conducting interviews with software engineers with AI exposure. This subjective strategy was expected to enable a topic of discussion according to the views of the software experts about housing retrofit.

The data was collected via online interviews with eight software experts with AI exposure, based on a semi-structured questionnaire. Interviewees were selected based on convenience, ensuring the suitability for data collection. The questionnaire outlined the retrofit processes and applicable challenges in respective phases. The interviewees were asked to comment on the potential of AI in addressing the retrofit challenges and using AI for optimizing existing processes. Overall, the study expected to produce a shopping list of potential AI use cases. The interview data was transcribed and qualitatively analyzed with NVivo software.

3. Findings

3.1 Introduction

Eight interviews were conducted with software industry experts in different domains. They were briefed about housing retrofit, retrofit stages, and examples of challenges in each retrofit stage. Further, the literature definitions of artificial intelligence and sub-areas of artificial intelligence were briefed. A study carried out by Abioye et al. (2021) was given to them as a guidance note if they needed to prepare for the interview. This article shows potential interactions between artificial intelligence and construction with a mind map. The potential advantages of artificial intelligence in housing retrofit were brainstormed under ten stages for each interviewee. Finally, they were consolidated. In addition to the AI potential in retrofit stages, the limitations of using AI were also discussed.

Table 1: Demographics of the participants – 01

Interviewee	**01**	**02**	**03**	**04**	**05**
Age	40-50	25-35	30-40	40-50	25-35
Gender	Male	Female	Male	Male	Male
Education	Masters	Bachelors	Bachelors	Masters	Masters
Specialization	Cyber security	Web development	Programming	Data Science	Project Mgt.

Table 2: Demographics of the participants – 02

Interviewee	**06**	**07**	**08**
Age	30-40	40-50	40-50
Gender	Male	Male	Female
Education	Masters	Masters	Bachelors
Specialization	DevOps	Cyber Security	Programming

The above table shows the demographic details of the eight interviewees. Seven of them are employed in the UK or European institutes/companies. One interviewee is a master's student at a UK university.

3.2 Problems in Housing Retrofit Projects

Table 3: Problems in housing retrofit

Theme	**Problems**
Financial	1. High cost of retrofit (TheIET, 2020). 2. Long payback periods (Wilson et al., 2015). 3. Difficulty in finding finance (Baumhof et al., 2018) 4. Sunk the cost of current upgrades (Ma et al., 2022). 5. Cost of information of retrofit (Ma et al., 2022).
Technical	1. Poor trust of the contractors (UKGBC, 2021). 2. Lack of professionals in retrofit (DBEIS, 2021). 3. Hard to heat houses (Liu et al., 2022) 4. Supply chain problems (Miller et al., 2018). 5. Too commercial approaches (Broers et al., 2019).
Governance	1. Unclear government policies (TheIET, 2020). 2. Unclear government processes (Ma et al., 2022). 3. Difficulty in obtaining planning approvals (Nelson, 2023)

Personal	1. Inability to justify retrofit (Lutzenhiser, 2014; UKGBC, 2021). 2. Investment-focused retrofit, not benefit-focused (Alabid, Bennadji, and Seddiki, 2022). 3. Uncertainty of outcomes (Ma et al., 2022). 4. Resistance to change (Ma et al., 2022). 5. Not realizing the need (Damigos et al., 2021) 6. Disruptions during retrofit (Broers et al., 2019)
Social	1. Family opinions against retrofit ga(Ma et al., 2022). 2. Negative social influence (Liu et al., 2022) 3. Previous bad experiences (Hope & Booth, 2014) 4. Poor stakeholder confidence (Rickaby, 2019).

The problems in housing retrofit projects were identified by the literature on different themes by different researchers. For the data analysis purpose of this study, the following problem themes were summarized. The key problems sourced from the literature are presented. However, the number of problems can be higher than this.

Other than the above, quality of information, modeling information for different requirements, stakeholder collaboration, reliability of the information, accessibility of information, the higher scope of work, low risk, simplification of presentation, and adaptability were the prominent solutions potential with artificial intelligence according to the data analysis.

3.3 Solutions from Artificial Intelligence

Table 4: Solutions from Artificial Intelligence

Themes	**Solutions**
Automation	Design automation through AI Improving health & safety - robotic automation Less human involvement in construction Certification by AI with provided data Automating facilities management functions Automated household equipment with AI Simplifying process through automation
Accuracy	1. Improving accuracy and reliability 2. Accurate bidding by the contractors 3. More accurate assessment through AI models 4. Higher accuracy of information with AI
Personal-station	1. Modelling information for different requirements 2. Understanding client requirements more effectively 3. Personalised information for decision-making 4. Recommending customised retrofit 5. More personalized designs to client requirements.
Objectivity	1. Unbiased analysis of suppliers with AI 2. Unbiased guidance for contract administration 3. Efficient dispute resolution with unbiased AI 4. More productive and objective certification process.
Optimization	1. Design optimisation through AI 2. Finding the best contractors with unbiased AI 3. AI will help lawyers to optimize their work 4. High-speed work with optimised methods/tools

Efficiency	1. The efficiency of processing information 2. Reducing the procurement duration drastically 3. Executing contracts online more efficiently 4. Working more hours with robotic processes

Other than the above, quality of information, modeling information for different requirements, stakeholder collaboration, reliability of the information, accessibility of information, higher scope of work, low risk, simplification of presentation, and adaptability were the prominent solutions potential with artificial intelligence according to the data analysis.

4. Discussion

4.1 Themes of the findings

First, the problems of housing retrofit can be themed under financial, technical, governance, personal, and social. The potentials of artificial intelligence were themed under automation, accuracy, personalization, objectivity, optimization, and efficiency. It is important to note that none of these themes are exhaustive and there can be further themes or items under these themes. Further, they may be presented in different combinations. For data analysis, the themes and the problems of housing retrofit are considered one by one. Then the potential of artificial intelligence is considered for each problem in the following section of discussion.

4.2 Financial problems of housing retrofit

The high cost of the retrofit and the long payback period are two of the main finance-related problems in housing retrofit. Artificial intelligence may be able to reduce the cost of the retrofit and reduce the payback period with automation, optimization and improving the efficiency of retrofit processes. For example, automation will be able to reduce human involvement, which reduce the human resources cost while improving efficiency through increased working hours. Further, AI will ease the finding of finance for retrofit while reducing the cost of information.

4.3 Technical problems of housing retrofit

The technical problems of housing retrofit include poor trust in contractors, lack of professionals, and too commercial approaches to retrofit. Objectivity is one of the highlighted potentials of artificial intelligence. This will reduce the trust issues and objections of homeowners to commercial approaches. With the help of AI, homeowners will be facilitated with more reliable information. Accordingly, commercial approaches will not work if they are misleading. Further, as most of the processes may be able to automated with AI, the problem of a lack of professionals will be mitigated.

4.4 Governance problems of housing retrofit

The problems related to governance include unclear government policies and processes as well as the difficulties of obtaining planning approvals. Considering the potential of artificial intelligence, AI will be helpful in the personalization of this information to the homeowner. Accordingly, the information related to the government policies will be clearer. Automation and efficiency of the processes with AI will help to obtain planning approvals more easily and efficiently.

4.5 Personal problems of housing retrofit

Problems related to the personal characteristics of the homeowner are diverse. These problems include uncertainties, difficulties in justification, personal behaviors, and so on. It is not clear how these can be addressed with the potential of artificial intelligence. However, if these are involved with disseminating information, those problems can be able to be addressed with artificial intelligence. Mainly, problems such as difficulties in justifying the retrofit decision may be addressed by providing more personalized information about the homeowner's circumstances. In brief, accuracy, objectivity, and personalization of information will be the key drivers of solving personal problems with artificial intelligence.

4.6 Social problems of housing retrofit

Family opinions about the retrofit, negative social influence, previous bad experiences, and poor stakeholder confidence are another few problems of housing retrofit. The interviewees have noted improved stakeholder collaboration with the help of artificial intelligence. Importantly, the objectivity of information can be noted. As the AI is deemed to be not biased towards any party, the homeowners may trust the opinion of AI rather than the social influence. Further, the information presented by AI will be more accurate than the socially obtained information by the homeowner.

The findings of the study are summarized in the below-mentioned figure, focusing on the highlights. The middle row comprises the retrofit problem themes and the other two rows show the main potentials of artificial intelligence. The arrows are drawn to show the main potential of artificial intelligence to solve housing retrofit problems.

4.7 Summary of the findings

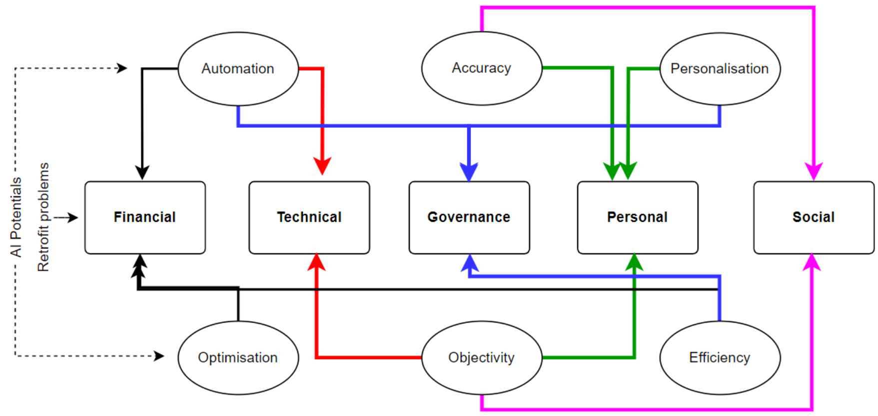

Figure 1: Retrofit problems and artificial intelligence potential.

The retrofit problems are categorized under the themes of financial, technical, governance, personal, and social. The potential of AI is identified as automation, accuracy, personalization, optimization, objectivity, and efficiency. Financial problems can be addressed with automation, optimization, and efficiency. Technical problems can be best supported with mainly automation and objectivity. Governance problems may get help from automation, personalization, and efficiency aspects of AI. Personal problems can be addressed with accuracy, personalization, and objectivity, which will improve the homeowner's confidence. Social problems can be addressed with mainly objectivity and accuracy.

4.8 Limitations of Artificial Intelligence

There are potential limitations of artificial intelligence, as discussed by the participants. However, these existing limitations may be solved as the technology evolves as AI is still at a growing stage. For the housing retrofit industry, poor quality of AI output, overreliance on AI, security, unemployment, and understanding human minds can be noteworthy limitations. The following table summarises the identified limitations of artificial intelligence to use in addressing the problems of housing retrofit.

Table 5: Limitations of artificial intelligence

	Limitation	Description
1	Quality	Poor input data resulting in poor AI output
2	Risk	AI technology going out to the wrong hands
3	Responsibility	Problems of the responsibility of AI actions
4	Cost	Cost of the AI technology
5	Overreliance	People being misled by AI
6	Security	Cyber security threats
7	Privacy	Privacy of the people being shared
8	Unemployment	People might lose their jobs
9	Personalization	To what extent does AI honor personal preferences
10	Dependability	Inability to fully depend on AI technology
11	Control	The risk of uncontrolled AI is not explored
12	Cognition	AI will not be able to read the human mind
13	Scope	Uncertainty of the scope of the AI potential

5. Conclusion

Artificial intelligence has become a buzzword in current technological discussion, paying attention to the potential of the technology. It is predicted that AI technology will revolutionize the way things are operated in the future, starting from today. Housing retrofit is considered of critical importance today, due to its influence on carbon emissions. Housing retrofit is observed with poor progress while the other sectors are showing considerable progress. Considering this, the importance of driving housing retrofit is established in the context of the sustainability agenda.

This paper has focused on how artificial intelligence will influence the retrofit processes and address retrofit challenges. The study has identified several themes of housing retrofit problems from the literature. Further, interviews were conducted with the software industry experts to brainstorm how artificial intelligence could address the challenges of housing retrofit and change the processes. As per the data analysis and discussion, artificial intelligence has some potential in some of the retrofit problem areas. However, as the interviewees commented, there can be negative consequences of artificial intelligence if not controlled properly. For example, over-reliance on artificial intelligence can make things go out of control of the humans. Another risk is privacy threats. If the technology goes into the wrong hands, there will be further negative consequences. However, it is still unable to tell the magnitude of the potential or risk of artificial intelligence. Every interviewee agreed that AI is not something to be afraid of or ignored. But it should be used wisely to make the world a better place. In terms of housing retrofit, AI will create more opportunities and solve some of the problems discussed above in detail.

In brief, the study has used a rather generic approach to retrofit problems and artificial intelligence as this technology is still at a growing level. In this case, further discussion will be required. However, it is expected that this paper will be a great conversation starter in the field of housing retrofit as well as artificial intelligence.

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CLIMATE CHANGE

ICSBE 2023-33

ANALYSIS OF THE IMPACT OF CLIMATE CHANGE ON STORM SURGES AND GLOBAL EXTREME EVENTS IN THE 21st CENTURY

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Abstract: An increase in mean sea level rise due to global warming and changes in weather patterns drive extreme sea levels such as storm surges as well as likely intensity and frequency of them. Over the recent period, significant effort has been encountered in enhancing the knowledge and identifying the reasons for the unprecedented storm surges in the 21st century. The post-disaster investigations conducted in several extreme events around the world such as Atlantic hurricane Katrina (2005), Indian Ocean cyclone Nargis (2008), and North Pacific typhoon Haiyan (2013), have raised the flag that sea level rise due to climate change and increased sea surface temperature may cause a significant effect on increasing of storm surge height and its intensity. The 6th assessment report of the Intergovernmental Panel on Climate Change (IPCC- AR6) states sea level rise is persistent throughout the 21st century and the projected global mean value will be in the range of 0.28-0.55m greater than the contemporary value under low carbon concentration scenario by the year 2100 due to thermal expansion of oceans and the polar glacial ice melting. Further, in line with IPCC-AR6, temperature may increase by 1.5°C (higher confidence level) at moderate to high carbon concentration scenarios. This will lead to a likely reduction of return periods of global extreme storm events by the end of the century. i.e. once in a hundred years, extreme events could occur every year. Consequently, it is undeniable according to the projected values of sea level rise and the temperature change, this challenge will be unrelenting. Hence, this paper focuses on the in-depth qualitative analysis of the impact of climate change on storm surges. Global extreme events over the last two decades will also be investigated to figure out how this global phenomenon has enhanced their severity.

Keywords: Storm surge; Climate change; Sea Surface Temperature; Sea level rise; IPCC-AR6

1. Introduction

Storm surge is an abnormal rise of water level generated by a storm and is produced by the accumulation of water pushed towards the coast by violent winds. If the tide level is at its maximum, severe storm surge conditions are expected due to a combination of both thus subsequent acute landfall would result in Catastrophic coastal flooding. According to the post-disaster investigation records of the past few decades highly intensified storms were observed in coastal regions remarkably in the 21st century all over the world resulting in a large number of human casualties and multi-billion-dollar financial loss. Following the substantial evidence provided by the Sixth Assessment Report of the Intergovernmental Panel for Climate Change (IPCC-AR6), the National Oceanic and Atmospheric Administration (NOAA) in the United States, states with medium to high confidence, that anthropogenic global warming has made a significant impact on enhancing storminess all over the world. Current mitigation measures in place will be insufficient to combat the extent of the adverse effects caused by extreme events to protect the people and their assets as well as the surrounding environment.

This paper will focus on the in-depth analysis of meteorological factors driven by climate change and their subsequent adverse effects on storm surges. Recent super storms which marked the history of the last two decades of the 21st century will also be rigorously analyzed to distinguish and rationally imply how they prevailed by anthropogenic climate change.

1.1. Impact of climate change on storm surges

Storm surge is directly driven by the integration of a great number of factors such as intensity and the magnitude of the storm, sea depth, direction and the velocity of the wind, shoreline topography, and many more atmospheric attributes (Ian et al. 2023). The intensity and the magnitude of the storms are predominant out of these influencing factors and according to the IPCC AR6 states with medium to high confidence, these are significantly amplified by the Global Mean Sea Level (GMSL) rise and the increasing Sea Surface Temperature (SST).

1.2 Global Mean Sea Level (GMSL) Rise

Global warming led by anthropogenic emission of heat-trapping Green House Gas (GHG) has caused the expansion of the ocean waters and melting polar ice caps and consequently, GMSL rise has been unrestrainable (NASA's Goddard Space Flight Centre satellite data 1993- present). According to IPCC AR6, large ice sheets melting in Antarctica and Greenland have been noticeably accelerated during the past two decades.

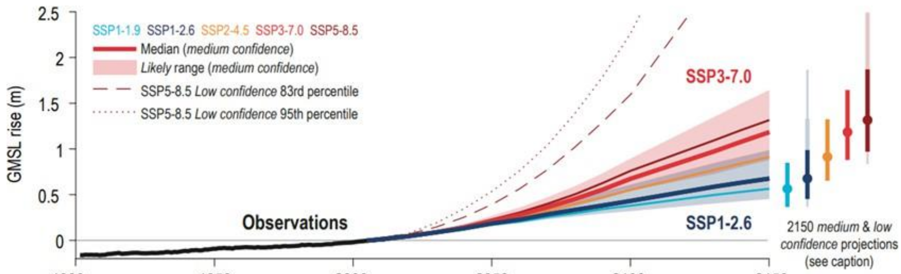

Figure 1: Global mean sea level (GMSL) changes on different time scales and under different GHG Concentration scenarios (IPCC-AR6).

Figure 1 depicts that in recent years sea level rise has been sped up and this will persist with exponential growth influenced by the SSP3-7.0 Scenario (Shared Socio-Economic Pathways defined by higher GHG emission-IPCC AR6) throughout this century and even after. Further, expertise projections outlined in AR6, have already alarmed that by the year 2050 sea level will rise by 10cm-25cm and this natural phenomenon is highly undetermined thus it will be significantly dependent on the accretion of GHG over the forthcoming decades.

Some future predictions explain under low GHG accumulation, sea level rise will be 3-8mm/year by 2100, however, if the ascending global warming persists, significant acceleration such as 5 times the present rate will arise due to the retreat of the ice sheets in south pole (IPCC AR6). A new research publication by IPCC, SROCC (Special Report on the Ocean and Cryosphere in a Changing Climate, 2019) affirms from 1901 to 2018, GMSL was driven by the summation of the individual components of ocean thermal expansion (38%) and melting glaciers in polar regions (41%). Batchelor & Christie (2023), a research team from Newcastle University have also stated in their new research, that the rate of ice sheet retreat in Antarctica will be faster at 600 meters per day which is 20 times than previously under present climate warming.

Further, IPCC AR6 disclosed regardless of the extent of the sea level rise even a trivial change in the global average may result in a high level of risk due to enhanced severity of storm surges and the landfall as well as the frequency. Moreover, experts forecast that if the current trend of warming extends, despite the GHG emission, by the year 2050 extreme sea level events with once in a hundred return period may occur yearly at 20-25% of locations. However, by 2100 as the emission matters, for low GHG emissions annually 60% of locations and for soaring emissions 80% of locations (IPCC AR6).

In Weather Research and Forecasting (WRF) and predictive models for storm surge simulations, the majority of researchers principally use integrated models of Shallow Water wave Equations (Non-linear first-order partial differential equations) derived from two physical conservation scenarios. i.e. mass and momentum conservation equations (Navier-stokes equations) along with bathymetry and the topography data to simulate the storm surge with future climate attributes (Sabunas et.al 2022).

Figure 2 illustrates the 1-D domain (x direction only) sketch used by Setiyowati and Sumardi (2019) for numerical simulation revealing the average water depth (D) at the shallow water region is directly proportional to the generated wave height (η) above the average water level. Hence, average water depth enhanced by associated sea level rise driven by global warming exacerbates the wave heights and subsequent landfall at extreme storm events.

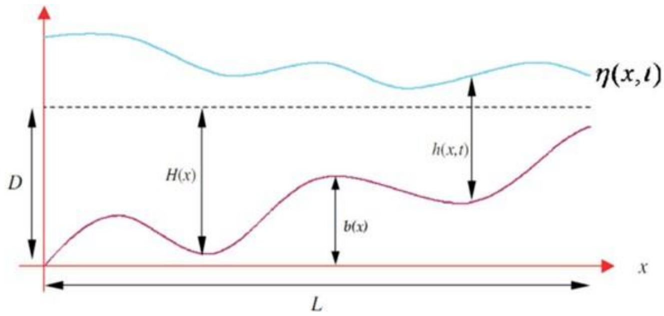

Figure 2: Domain sketch of the 1-D shallow water wave model (Setiyowati and Sumardi (2019).

Murdukhayeva et al. (2013), developed a system to simulate the future coastal inundation in two national parks on the north-eastern coast i.e. Cape Cod National Seashore, Massachusetts & Assateague Island National Seashore, Maryland/Virginia to assist the governing bodies to preserve the natural and cultural values of these respected vicinities. Sea level rise enhanced by anthropogenic global warming and the subsequent extreme storm surge were the main factors embedded in this developed methodology to evaluate the flood risk at the sentinel sites. In this research, authors integrated three numerical models i.e. Sea Level Affecting Marshes Model (SLAMM), Sea- Lake and Overland Surges from Hurricanes (SLOSH) model, and the Modified Bathtub Model. Mainly, the SLAMM model is a mathematical model that has been used since the mid-1980s that employs the digital sea level elevation data obtained by the Real-Time Kinematic Global Positioning System (RTK GPS) to reliably evaluate the likelihood of impact on the wetlands and the shorelines by the long-term sea level rise (U.S Climate Resilience Toolkit, 2021).

Further, the Bathtub Model is a mapping tool developed by the NOAA Office for Coastal Management to map the inundation triggered by extreme storm surges under sea level rise. The output of this modeling approach was significantly definitive compared to the real-time inundation at the sentinel sites, thus the simulations for the future too.

Liu et al. (2021) used the FUNWAVE-TVD, fully nonlinear Boussinesq nearshore wave (fairly long and weakly no-linear waves) model (Shi et al. 2012), to simulate the Annual Exceedance Probabilities (AEPs) of 1% & 10% of the storm flooding in future extreme events at the coastline of Connecticut-USA to come up with a solid outline of a design for the coastline protection structures. Researchers included sea level rise at the subject location by 2050 in their simulation of periodic storms along with the boundary conditions from the validated coupled model, FVCOM-SWAVE (Finite Volume Community Ocean Model-Surface Wave). The outcome of the simulation showed a clear augmentation of the inundation with enhanced storm surges with sea level rise in the 2050 scenario and 10% AEP is exacerbated to 50% AEP. Further, they concluded this result is highly accurate and therefore can be validated to apply in the design of sea defense structures when executing protection measures for future extremes prevailed by the sea level rise.

Correspondingly, on numerous occasions can be encountered which by researchers around the world have proved by predictive modeling in light of global warming that there is a distinct relationship between sea level rise and the destructive attributes of storm surges. As this climate phenomenon is unprecedented and momentous, should be vitally considered in the analysis of the impact would compel on storm surges and the adaptation to future extremes.

1.3 Enhanced Global Mean Sea Surface Temperature (GMSST)

Sea Surface Temperature (SST) is defined as the temperature of the water at the surface of the ocean. This climate phenomenon is leading to many weather characteristics regionally and globally. The SST is a regional climate parameter and varies with the latitude where the warmest is closer to the equator and the coldest at the polar regions (United States Environmental Protection Agency,2023).

Figure 3 demonstrates how the global average SST changed from 1901 to 2020. This was produced using combined measurements of direct and satellite observations and the "+" mark on the map signified the positive trend of SST. Further referring to the United States Environmental Protection Agency, in most parts of the ocean around the world, SST has been noticeably increasing for the past three decades.

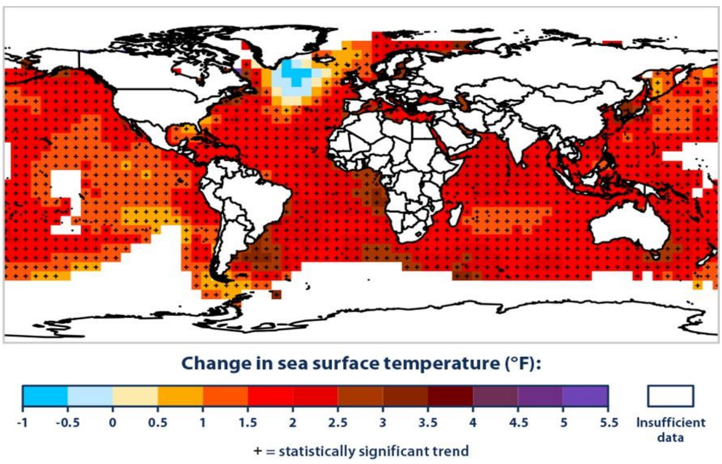

Figure 3: Change in Sea Surface Temperature, 1901–2020 (Data source: IPCC AR5, 2013).

As claimed by the IPCC 5th Assessment Report (IPCC-AR5, 2013), SST has been increasing since the start of the 20th century (Very high confidence) and authors have shown the fidelity of this climate phenomenon for the future by the output of Numerical Coupled Model (CMIP6). They further state these SST projections for 2100 are virtually distinct and will depend on the future GHG concentration scenarios (IPCC AR6). Further, IPCC AR6 states that 83% of the GMSST will be warmed under SSP1-2.6 while 98% under SSP5-8.5 by 2100. Table 1 and Figure 4 illustrate the Global Mean Sea Surface Temperatures (GMSST) very likely projections for the future under different SSPs (Shared Socio-economic Pathways).

Table 1: GMSST projections by 2100 abstracted from IPCC-AR6

GHG emission scenario	Global mean SST projection by CMIP6 (^{0}C)
SSP1-2.6	0.86
SSP3-7.0	2.19
SSP5-8.5	2.89

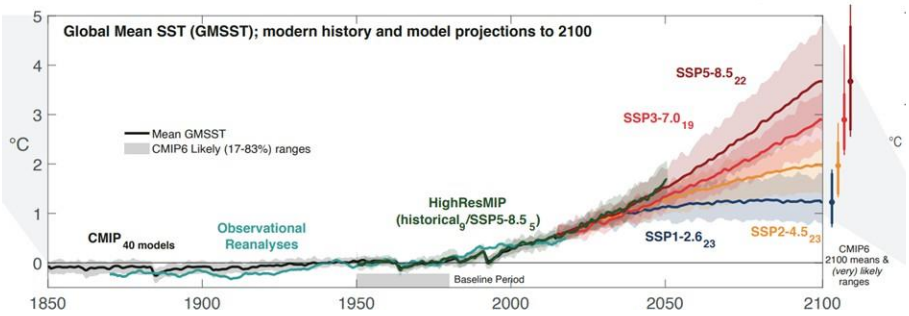

Figure 4: GMSST changes with time (IPCC-AR6) by the end of the century.

The World Meteorological Organization (WMO), Dr. Rea, Anthony, Director for infrastructure at WMO & head of the Global Climate Observing System, highlighted that the global SSTs are exceptionally high according to the latest datasets thus alarm for the future weather extremes including intensified cyclonic activities due to the combined effect of high precipitation and enormous heat energy absorption by the sea. These statistics are intelligible evidence for the substantial impact of climate change upon the regional and global SST which will make a severe impact on storm surges and other attributes. Mainly warmer Sea Surface Temperatures intensify the storm surges as well as their duration while the cooler SSTs downscale these attributes (Lavender et al. 2018). The severity and the perseverance of the storms are principally governed by the warm ocean surface and the low wind shear (the difference in wind speed between the upper and lower layers of the storm). In recent times, numerous pieces of research have been encountered around the world, to understand the collaterality of the SST and the storm surge and their intensity. Warm ocean evaporates water from the sea surface thus creating a low-pressure region as the water vapor rises. Soaring convective clouds in bands (rainbands) are formed around the eyeball (the lowest pressure point and the storm center) of the storm subsequently cold air violently churns into the low-pressure region. As the process succeeds, latent heat is set free at the cooling process of water vapor, in consequence, wind (trade wind) swirls and grows absorbing the latent heat and the warmer sea surface [Figure 6: *NASA, Global Precipitation Measurements (GPM), 2023*]. The Coriolis effect (deflection induced by the earth’s rotation. Spins clockwise in the Southern Hemisphere and counterclockwise in the Northern Hemisphere) further induces the trade wind speed during the storm rotation (National Geographic Channel). According to the Saffir-Simpson Hurricane Scale (SSHS) by NOAA, storms are categorized depending on the wind- speed (See Figure 6).

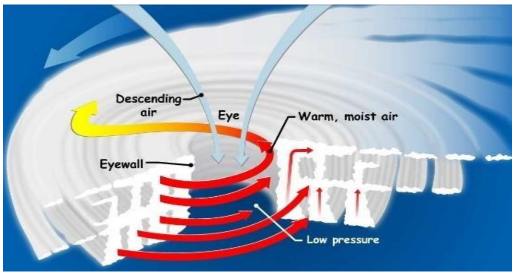

Figure 5: Structure of the storm.

Category	Wind Speed (mph)	Damage at Landfall	Storm Surge (feet)
1	74-95	Minimal	4-5
2	96-110	Moderate	6-8
3	111-130	Extensive	9-12
4	131-155	Extreme	13-18
5	Over 155	Catastrophic	19+

Figure 6: Categorisation of storms According to the SSHS.

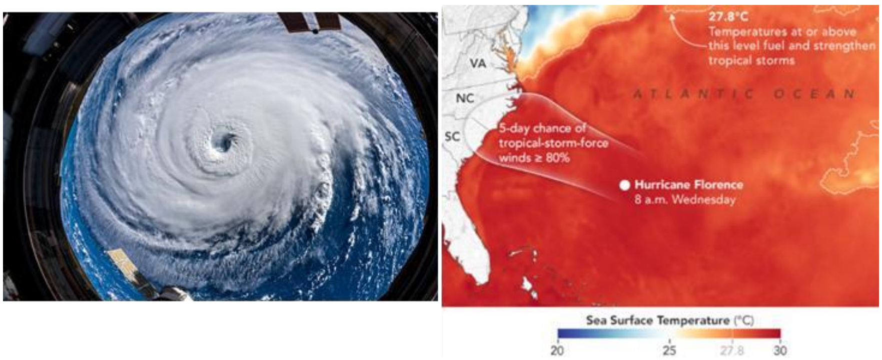

Figure 7: Left: Hurricane eye, right: Map of the SST of Florence heading for landfall [*NASA Earth Observatory images*, 2018].

Mainly tropical and subtropical ocean basins fuel up the storms above 26^{0}C since the driving energy acquired during the energy transfer that resulted from the deep convection of the moist atmosphere above this temperature (Chan, 2022). Figure 7 (right) shows an exemplar of the SST (27.8^{0}C) of Hurricane Florence (2018) one of the longest-lived Hurricanes in US history it was well above the threshold where the SST anomaly was 0.5-1.5 ^{0}C compared to the yearly average (NOAA). Figure 7 (left) [*NASA Earth Observatory images*, 2018] illustrates a very clear eye view of Florence showing evidence of a low-pressure region followed by high SST.

Webster et.al, (2005) scrutinized the span of 35 years of tropical storms and tracked the number of days they continued and their intensities during their landfall. The number and the percentage of storms that reached categories 4 and 5 were largely detected by the authors in the North Pacific, Southwest Pacific, and Indian Ocean basins under increased SST.

Vecchi et al (2008), also conducted numerical simulations and statistical analysis for Atlantic basin hurricanes for the past 35 years from 2005 to understand how the absolute SST (assuming a uniform ocean warming) and the relative SST (under a limited area of ocean warming while the outer ocean is unaffected) influence on the storm attributes under enhanced SST is driven by the anthropogenic climate change. The authors observed that relative SST is the key to augmenting the storminess and this is proved by the positive interdependence of Accumulated Cyclone Energy (ACE) amplified by higher SST and the Power Dissipation Index (PDI) and PDI has approximately doubled over the range of years they considered under enhanced relative SST. According to the climate model projections, if these associations remain unchanged the catastrophic potential strength led by PDI will be roughly increased by 300% by the end of the 21st century in Atlantic basin Hurricanes (Vecchi et al. 2008).

Moreover, Ramsay & Sobel (2011) from the Massachusetts Institute of Technology observed the same as Vecchi et al. 2008, the dominance of the relative SST in enhancing PDI of Atlantic Basin Hurricanes, in their simulation using a Weather Research and Forecasting-Single Column Model (Geophysical Fluid Dynamics Laboratory, NOAA) using two models i.e. relative and absolute SST and also to foresee the future weather phenomena induced by the climate change. However, they suggested in climate projections with enhanced global warming, absolute GMSST will be elevated and become dominant over the relative GMSST in individual ocean basins. Despite the grey areas in this subject matter, either relative SST or absolute SST will amplify the severity of future storms and the subsequent storm surges under anthropogenic climate warming.

Vickery et al. (2000) investigated the potential impact of the SST based on the projected RCP (Representative Concentration Pathways) proposed by the IPCC depending on the degree of Greenhouse gas concentration in the future in Atlantic and Gulf coasts to foresee the danger associated with the elevated weather attributes. Empirical Track Model and the Sea, Lake, and Overland Surge from the Hurricanes model (SLOSH) were employed to predict the storm intensity and surge level. Under all four RCP scenarios, fiercer and an increasing tendency of future storm surge levels were observed in all locations considered.

Moreover, the proportion of Category 4 & 5 storms and the projected intensity has been increasing advancing higher storm surges, destructive wind speeds, and acute rainfall rates. However, according to many climate predictive models, low-intensity cyclones proportionally will decrease hence annual total may be deducted or continue to exist the same (*NOAA, Climate. gov.*, 2021). Figure 8 depicts 95% of the significance level of all the extreme events with the highest wind speed of 175km/hr while 200-250 km/hr have doubled in total and over 250km/hr events in severity scale have been tripled. Despite some shifts requiring further scrutinizing, it can be seen global warming is steering more intense storms and subsequent storm surges with devastating aftermaths (Ramstof et al. 2018).

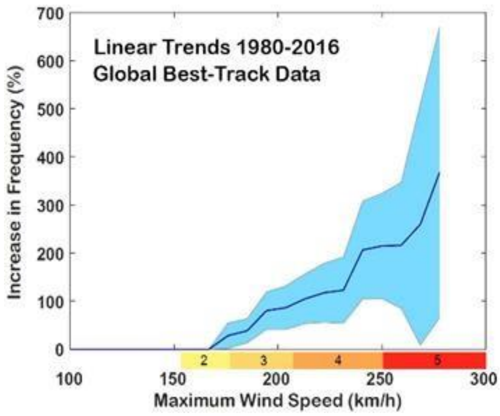

Figure 8: Increase in the number of tropical storms from 1980 to 2016 (Ramstof et al. 2018).

2 Analysis of past global extreme events and the impact of the climate change on them

Thus far it is evident by careful observations of many extreme weather events that took place in the past few decades that tropical storms' severity and frequency have been increasing due to weather attributes triggered by global warming. In this section, authors will comprehensively investigate a few global extreme storms during the past two decades which made a formidable history in weather records.

2.1 Hurricane Katrina (August 2005):

Hurricane Katrina was a killer natural disaster that marked US history as the costliest Hurricane causing financial damage of approximately US$ 161 billion and 1833 fatalities. It was also one of the five most destructive storm events to ever hit the United States [*NOAA*, *National Weather Service (NWS)*, 2005]. Hurricane Katrina was formed as a Topical cyclone on 24th August 2005 due to a low-pressure zone (tropical depression) over the south-eastern Bahamas.

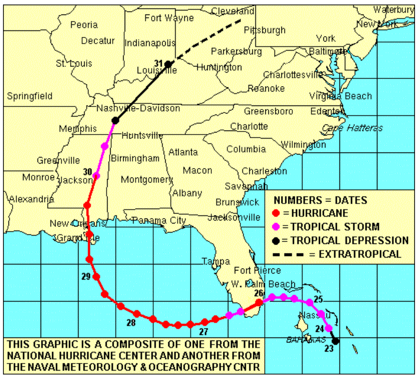

Figure 9: Hurricane Katrina storm track by Naval Meteorology USA.

Further westward movement over the warmer ocean of the Gulf of Mexico, the storm swiftly intensified to Category 5 with a persistent wind speed of 175mph then downscaled to Category 3 before the landfall at Louisiana (New Orleans) with sustained wind speeds of 125mph and 920.2 mb & 972.2 mb and the highest storm surges recorded were 18.7ft (5.7 m) to make overpowering devastation in US history. Irish et al. (2014), simulated a hypothetical Hurricane Katrina to visualize the effect if this occurred in 1900 and compared it to the actual devastation caused in 2005 in New Orleans. Authors observed in the surge simulation, 15%-60%lower flood elevation in hypothetical hurricane Katrina in 1900 than the real case in 2005 thus the output suggests this has been predominantly induced by the mean sea level rise enhanced by anthropogenic climate change.

Menas Kaftos and co-workers from George Mason University observed in their research using satellite data, above 30^{0}C SST on average over the month of August in 2005 [Figure 10: Left, *NASA*, (2008)] as well as 0.8^{0}C increment (Figure 10: Right) compared to the normal level (Dume, 2005). Hence it is evident, climate change-induced ocean attributes have magnified the destructive nature of Hurricane Katrina, consequently extreme storm surges and following landfall.

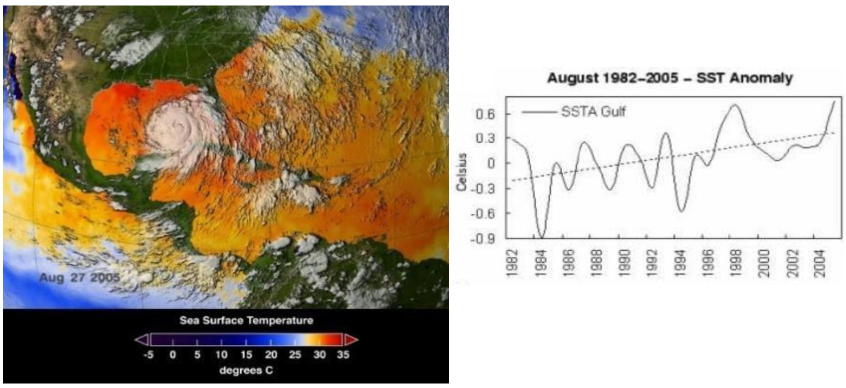

Figure 10: Left: Satellite image of SST of the Atlantic Ocean & Caribbean Sea on August 27, 2005. Right: 1982-2005 SST anomaly during August.

A group of researchers from the US Ocean Dynamic Modelling from the North Pacific National Laboratory (*NPNL,* 2021) produced high-resolution data to implement resilient and mitigation measures for the low-lying coastal communities by simulating Hurricane Katrina storm surge integrating future GHG emission scenarios (see Figure 11). The model output clearly showed the contrast of the storm surge between past and future climates which alarms the future.

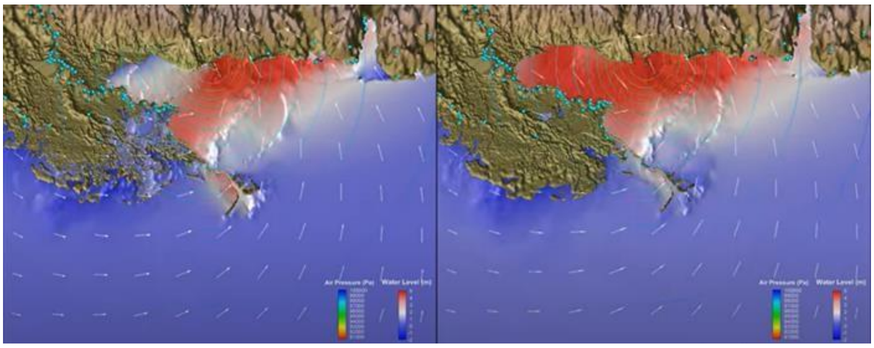

Figure 11: Hurricane Katrina simulation using FVCOM. Left: Storm surge integrated with real-time data without sea level rise. Right: Storm surge in future with 0.3m sea level rise (*NPNL,* 2021).

2.2 Cyclone Nargis (May 2008)
On 02nd March 2008 Tropical Cyclone Nargis (Category 4 in SSHS. See Figure 12) marked its landfall to become the worst natural disaster ever in Myanmar and the 8th deadliest storm in the world causing an estimated death toll of over 138,000 (Fritz et al. 2009). According to the estimation by the United Nations, the storm surge was between 3.5 m- 7.0m, and the sustained wind- speed towards Myanmar was 194 km/hr at its highest.

The Centre for Science and Environment (CSE), India stated after the post-disaster observations, "Cyclone Nargis is not just a natural disaster, but a human-made disaster caused by climate change"(Mwangi, 2008).

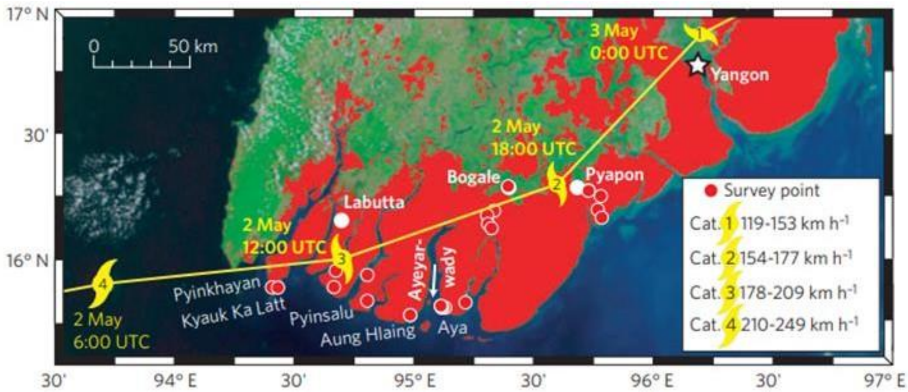

Figure 12: Flood overlay map & SSHS by NASA MODIS Rapid Response imagery (Fritz et al. 2009).

According to Wang et al. (2013), in their simulation utilizing CESM (Community Earth System Model), SST and the tropospheric warming in the Bay of Bengal (BOB) ocean basin has been augmented by anthropogenic activities, thus increasing the frequency of the Tropical Cyclones and their intensities. Further authors suggest that the reinforcing of resilience measures should be led by robust climate simulations integrated with climate change in the BOB thus in the Myanmar region.

2.3 Super Typhoon Haiyan (November 2013)
Typhoon Haiyan also called super typhoon Yolanda (Category 5 in SSHS) generated over the warmer sea surface in the western Pacific Ocean basin headed toward the Philippines to make unprecedented

devastation on 08th November 2013 and swept Leyte Gulf. It made history as the strongest tropical cyclone at the Landfall with an estimated maximum sustained wind speed of 195mph (315 km/hr) and a minimum pressure of 895 hpa at the eye of the cyclone (*stratusdeck*, 2016). These factors counted at the peak intensity of typhoon Haiyan subsequently triggered unusual behavior and an extreme storm surge of 5.0-6.0 m further augmented by steeper bathymetry of the Leyte Gulf to cause confirmed deaths 6300, 1062 were missing along with 28,688 injured people and economic loss of US$13 billion based on the statistics published by the Philippine National Disaster Risk Reduction Council (Athawes, 2018). Figure 13 (*CIMSS Satellite Blog*, 2013) illustrates the sustained SST of 29.5-30.5 ^{0}C of the Philippine Sea when Haiyan was about to make its landfall at the Leyte Gulf, and the depth of the warm water of the ocean was also stretched to abnormally deeper which massively intensified the storminess due to the release of latent heat (*stratusdeck*, 2016)

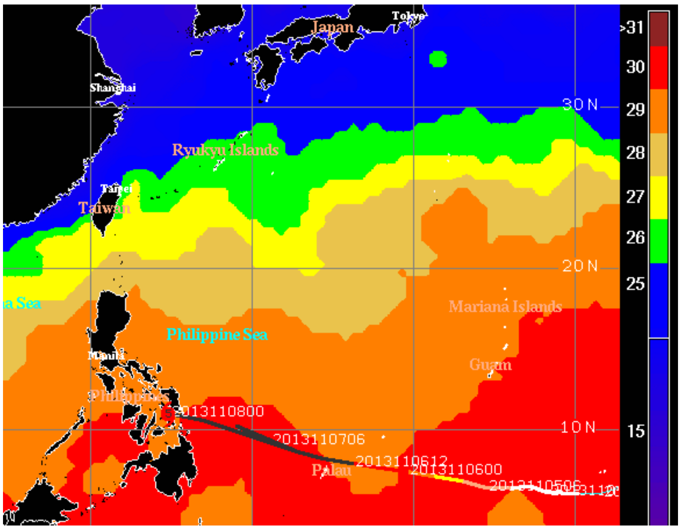

Figure 13: SST of the western Pacific Ocean during the formation of Typhoon Haiyan in November 2013 (*CIMSS Satellite Blog*, 2013).

It is evident that the real-time average SST was unusually higher in the Western Pacific Ocean during typhoon Haiyan, and this alarmed the future weather extremes either to be similar or greater as a consequence of anthropogenic climate change. Takayabu et al. (2015) employed distinct high-resolution regional climate models to simulate the pressure depression, storm surge, and wind speed of typhoon Haiyan. The authors used an ensemble model of a hypothetical natural climate without anthropogenic climate forcing and worst-case typhoons with real-time weather attributes of typhoon Haiyan. They observed the storm surge has increased by 20% in the real-time worst case of Haiyan compared to the hypothetical natural climate simulation thus it is convinced by these solid affirmations that the climate change and the severity of the storms are significantly correlated.

3 Conclusion

In this paper authors intensely analyzed the experimental studies and the case studies on past extreme storms that have been carried out by the experts in the field to reveal the impact of the amplified sea level and the sea surface temperatures induced by anthropogenic climate change on storm surges and the future projections. Further, in-depth research was carried out over past historical weather extremes in the 21st century and their real-time weather attributes to be strongly perceived, how climate change amplified those extremes to cost an immense number of human lives and enormous asset loss. Thus, the authors were able to reasonably discover that anthropogenic climate change and the intensity of the storms are intensely linked due to the profound influence of the precipitation rate over warmer sea surfaces and the amplified sea levels which trigger enhanced wind speed, intense rainfall, and subsequent extreme surges globally. However, further research is decidedly recommended to unlock the grey areas and exterminate the uncertainties.

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SPATIO-TEMPORAL ANALYSIS OF MODIS-BASED LAND SURFACE TEMPERATURE USING GOOGLE EARTH ENGINE (GEE) IN AMPARA DISTRICT

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Abstract: The comprehension of Earth's surface thermal behavior and its effects on environmental processes hinges on Land Surface Temperature (LST). In Ampara District, the summers bring sweltering heat and cloudy skies, whereas the winters are short, mild, and frequently accompanied by rain and predominantly overcast conditions. The climate in Ampara District remains persistently oppressive throughout the year, with average temperatures ranging from 23°C to 33°C, seldom dropping below 22°C or exceeding 35°C. This study conducts a spatio-temporal investigation of MODIS-based LST patterns, exploring the interplay between LST and Land Use/Land Cover (LULC) using Google Earth Engine (GEE) in 2023. Utilizing MODIS LST data with a spatial resolution of 1 kilometer and a temporal resolution of 1 to 2 days, the analysis incorporates LULC to elucidate the impact of various land types on LST. Results reveal significant fluctuations in daytime LST, reaching peaks from 27.8°C to 41.5°C, 27.6°C to 38.0°C, and 28.0°C to 38.2°C during April, May, and June 2023, respectively. Particularly in April, the highest daytime LST readings occurred on the 23rd, 17th, 15th, and 20th, recording 36.2°C, 34.9°C, 33.6°C, and 33.4°C, respectively. Similar trends were observed in June, with peak LST values on the 26th and 7th, reaching 38.80°C and 33.20°C, respectively. In contrast, January through March displayed the lowest LST values. Despite a Root Mean Squared Error (RMSE) and correlation coefficient (CC) of 0.96 and 0.97, respectively, zonal statistics identified the agricultural sector, particularly paddy cultivation, as the focal point for the most pronounced LST spikes. Various areas, such as residential zones, bodies of water, non-agricultural lands, and forests, exhibited diverse LST values. The research emphasizes the critical role of vegetation in mitigating the impact of LST, especially during peak heat days, offering valuable insights for urban planning, land management, and climate resilience strategies.

Keywords: Thermal; Spatial; Temporal; Zonal statistics, Environment

1. Introduction

In recent times, the issue of Land Surface Temperature (LST) has garnered substantial attention due to its detrimental impacts on human well-being, agriculture, and the balance of natural ecosystems. Capturing LST variability in space-time is crucial for developing effective strategies to mitigate its effects and develop adaptive actions. Especially, from 1956 to 2006 annual temperatures increased dramatically, up 0.13°C per decade, the acceleration seen by 2007 over the past century is twice the pace recorded by the IPCC in 2010. LST stands as an important indicator of the relationship between urban growth patterns and the temperature environment between Kesgin Atak, 2020). Thus, LST has found frequent application in urban heat island (UHI) analysis, which aims to understand the relationship between LST and land use/land cover (LULC) classes (Du et al., 2016).

Remote sensing (RS) data, especially from the Moderate Resolution Imaging Spectroradiometer (MODIS), provide valuable insights to examine LST propagation in regional LST associated with heat waves due to the high spatiotemporal resolution of MODIS data for the reason. It has been widely used in monitoring anomalies by Chen et al. (2016) used MODIS data to determine and test LST in Beijing, China, including intensity and spatial extent. Combining MODIS data with other environmental variables, such as Sun et al. (2019), obtained a more detailed understanding of LST dynamics with LULC. This integration further highlighted the dominant impact of LULC on LST depth and period, with rural areas showing extra seasoned-nounced and longer LST compared to rural areas however MODIS data from discovered satellite radiance imparts several advantages to LST evaluation. By detecting and reading LST anomalies, the occurrence and intensity of tropical events may be monitored. Additionally, the high temporal decision of the MODIS information permits for high-frequency detection, that is necessary to decide LST length and frequency. The long-term record of MODIS statistics enables the detection of developments in LST activities, which contribute to climate change impact assessment.

Several studies have shown the feasibility of using satellite-derived LST to estimate daily maximum air temperature This is demonstrated by the correlation between LST data obtained from the RS dataset and air temperature measurements different algorithms operate between (Guo et al., 2005). 2020) Many have proposed the use of LST (Long Short-Term) methods from an algorithmic perspective for RS data (Ermi-da et al., 2020). While many algorithms are straightforward to implement, they must provide users with important input data and measurement co-efficiencies, which are often not readily available but are often important to users to handle significant amounts of data. Thus, Google Earth Engine (GEE) was developed as an online platform that can enable RS users to perform advanced data analysis without increasing their local computing resources (Gorelick et al., 2017).

The present study attempts to investigate the spatio-temporal LST anomalies in the Ampara region using MODIS RS data through GEE. The resultant insights hold valuable implications for policymakers, urban planners, and local communities, facilitating the development of effective strategies to mitigate the ramifications of LST in the Ampara District.

2. Materials and Methodology

2.1 Study Area

Encompassing 20 Divisional Secretariat Division (DSD) within the boundaries of Amapra District, the study area is characterized by significant urbanization, particularly in the coastal DSDs of Kalmunai, Santhamaruthu, Karaithivu, Nintavur, Addalaichchenai, Akkariapattu, Alayadivembu, Thirukkovil, Pottuvi and Lahugala (Figure 1). Covering a land area of 449,552 hectares, this study area was inhabited by 649,402 individuals in 2012, as documented by the Land Use Policy Planning Department (LUPPD), in 2016. Amapara District's strategic location, favorable topography, and climatic conditions contribute to its emergence as a prominent national attraction.

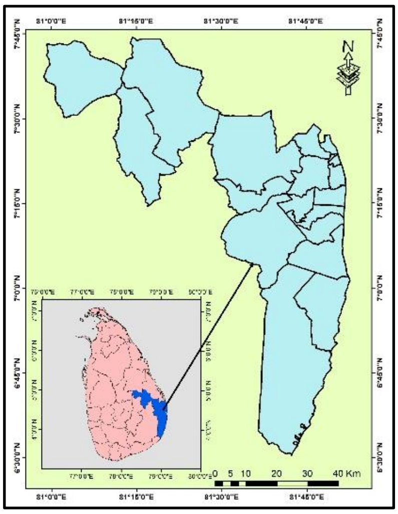

Figure 1: Map of Study Area.

2.1 Retrieval LST Using GEE

The MODIS data product furnishes daily LST and emissivity values within a 1200 x 1200 kilometer grid. These temperature values are obtained from the MOD11_L2 swath product. Beyond 30 degrees latitude, certain pixels may exhibit multiple observations meeting clear-sky criteria. In such instances, the pixel value is the average of all qualifying observations. The product includes day-time and night-time surface temperature bands, quality indicator layers, MODIS bands 31 and 32, and six observation layers. The data that MOD11A1.061 Terra LST and Emissivity Daily Global 1km spatial resolution.

The MODIS data was acquired on 20 August 2023 from the web portal (https://developers.google.com/earthengine/datasets/catalog/MODIS_061_MOD11A1).
Retrieving LST using GEE involves utilizing the platform's capabilities for remote sensing data processing and analysis. The GEE website operates within the "Code Editor" section, enabling the composition and execution of JavaScript code (Figure 2). This code facilitates the utilization of satellite imagery from MODIS LST.

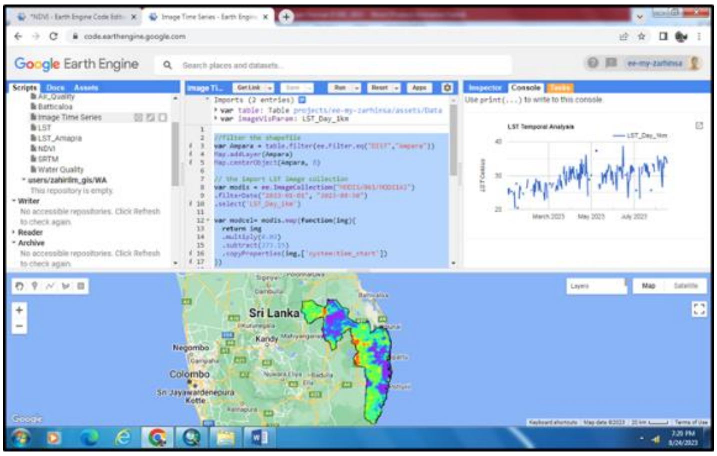

Figure 2: Using the GGE Code of LST in Amapara District.

JavaScript Coding of LST in the Ampara district using GEE.

```
//Filter the shape file
var Ampara = table.filter(ee.Filter.eq("DIST","Ampara"))
Map.addLayer(Ampara)
Map.centerObject(Ampara, 8)
// the import LST image collection
var modis = ee.ImageCollection("MODIS/061/MOD11A1")
.filterDate("2023-01-01", "2023-07-30")
.select('LST_Day_1km')
var modcel= modis.map(function(img){
  return img
  .multiply(0.02)
  .subtract(273.15)
  .copyProperties(img,['system:time_start'])
})
//Chart of LST temporal analysis
var tsc = ui.Chart.image.series({
  imageCollection : modcel,
  region : Ampara,
  reducer : ee.Reducer.mean(),
  scale : 1000,
  xProperty : 'system:time_start'})
  .setOptions({
    title : 'LST Temporal Analysis',
    vAxis : {title : 'LST Celcius'}})
  print(tsc)
  //image visualization
var mean = modcel.mean().clip(Ampara)
Map.addLayer(mean,{},'LST mean')
//Export image
Export.image.toDrive({
  image: mean,
  description: 'MODIS_June09_mean',
  region: Ampara,
  scale: 1000,
});
```

2.2 Land Use/Land Cover (LULC)

The LULC map for Ampara District was derived from data in the Lessons Learnt and Reconciliation Commission (LLRC) report (LUPPD, 2016). The initial dataset, which contained 25 subclasses from the LULC 2016 data, was reclassified into 20 DSDs LULC types as detailed. The distribution of these LULC categories across Ampara District is presented in Table 1.

Table 1: LULC in Ampara District (Source: LUPPD, Ampara (2016)

Main Category	**Subcategory I**	**Subcategory II**	**Approx. Extent (ha)**	**%**
Non-Agricultural lands	Service centers		1,025	0.2
	Industrial area		594	0.1
	Other		2,347	0.5
Home gardens			42,641	9.5
Agricultural Lands (Cultivated Lands)	Seasonal crops	Paddy	97,268	21.6
		Field crops	16,865	3.8
	Permanent crops	Coconut	1,162	0.3
		Cashew	411	0.1
		Sugar cane	6,570	1.5
		Rubber	880	0.2
		Other perennial crops	663	0.1
	Aquaculture		26	0.005
Forest	Natural Forest		144,080	32.1
	Forest Plantation		8,114	1.8
	Scrub Land		55,096	12.3
	Grass Land		19,715	4.4
Wet Lands	Marsh		2,058	0.5
	Mangrove		155	0.034
Other Lands	Vacant lands		3,346	0.7
	Unproductive lands		128	0.028
	Rock outcrops		16,237	3.6
	Sandy area (beaches, sand dunes, etc.)		1,590	0.4
Water bodies	Lagoon		5,502	1.2
	Tanks(major & minor tanks, natural ponds)		18,668	4.2
	Rivers and streams		4399	1.0

In 2016, the predominant features of Ampara District's landscape were agricultural zones, encompassing 27.6% of the region, and forests, spanning 50.6%. These two categories constituted the largest portions of the landscape. Following these were non-agricultural areas including homesteads, wetlands, water bodies, and other land types like vacant areas, unproductive land, rocky outcrops, and sandy areas, arranged in order of coverage. In contrast, wetlands covered a relatively small portion of the overall landscape, accounting for a mere 0.73% in total.

2.3 Zonal Statistical Analysis

Zonal Statistical Analysis (ZSA) in the ArcGIS platform involves analyzing the relationship between two spatial datasets within predefined zones or regions. ZSA holes significant value across diverse domins sush as urban planning, resource management, environmental analysis, social sciences, and public policy. It provides a way to examine how data vary across geographic areas, making it an important tool for decision-making and understanding habitat patterns. This analytical approach comparing LST and LULC classes can provide insight into how LULC diversity affects LST coefficients

(Kesgin Atak, 2020). In addition, this method computes a set of statistics for a raster data set with predefined regions or regions, such as MEAN, SUM, MIN, MAX, etc. Whenever there is a "MEAN" available LST of each LULC district or class.

3. Results and Discussion

LST data were collected during the first seven months of 2023 (January to July) to capture diurnal temperature variations. In addition, the study included LULC data in the analysis to investigate the effect of different LULCs on LST. The maximum MODIS data LST value is compared to the ground truth data for accuracy using two metrics: the Root Mean Square Error (RMSE) yields an accuracy of 0.96, while the Correlation Coefficient (CC) attains a high accuracy of 0.97. The results revealed significant variations in LST, where higher LST was recorded from the end of March to July. The peak LST, exceeding 35°C, occurred throughout April. In May, temperatures exceeding 40°C were recorded on a few days: the 8th, 13th, 20th, 26th, and 28th. Only three days of 6th, 14th, and 23rd in June had a maximum daily LST lower than 32°C, whereas all the remaining days experienced LST exceeding 40°C (Figure 3). Similarly in July. The results of the LST analysis indicate that the range between the maximum and minimum LST values is elevated in April, May, June, and July compared with January, February, and March. During the period spanning from January to March, the highest and lowest monthly LST were recorded as 16.7°C - 11.0°C, 20.1°C - 13.9°C, and 23.5°C - 14.4°C. The corresponding ranges of LST for these months were 5.7°C, 6.2°C, and 9.1°C, respectively. However, between April and July, the recorded LST values as 32.1°C - 20.4°C, 24.2°C - 15.7°C, 32.8°C - 20.5°C, and 25.5°C - 13.9°C (Table 2). The ranges compared correspondingly were higher during January to March. Nevertheless, over the research period spanning from April to July, the study area recorded average LST values exceeding 30°C. When comparing the maximum LST day 1 km values between 2022 and 2023, it is evident that the values for 2023 exceeded those for 2022 from January to July (Figure 4).

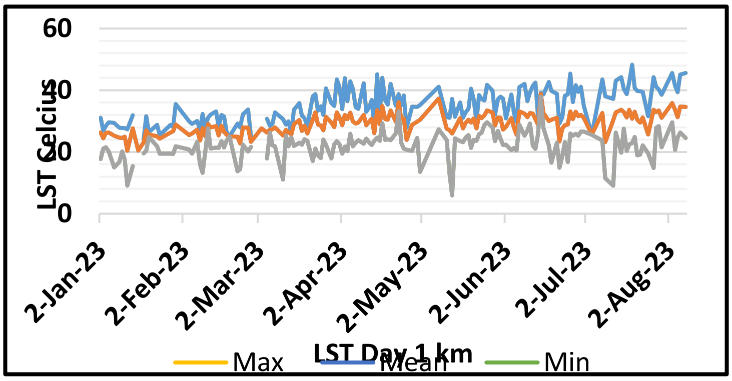

Figure 3: LST Temporal Analysis.

Vegetated regions, encompassing forests and agricultural lands, showcased lower LST values in contrast to urbanized areas and exposed soil. The investigation further pinpointed focal points of heightened LSTs, predominantly within densely urbanized locales and zones characterized by limited vegetation coverage.

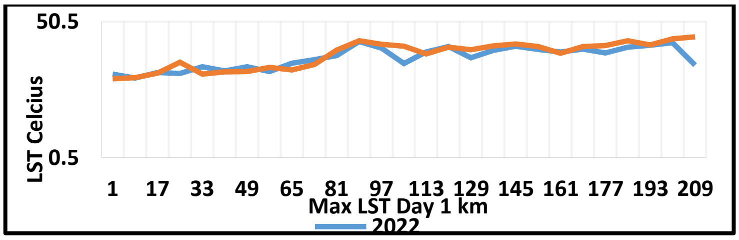

Figure 4: LST Maximum on Day 1 km.

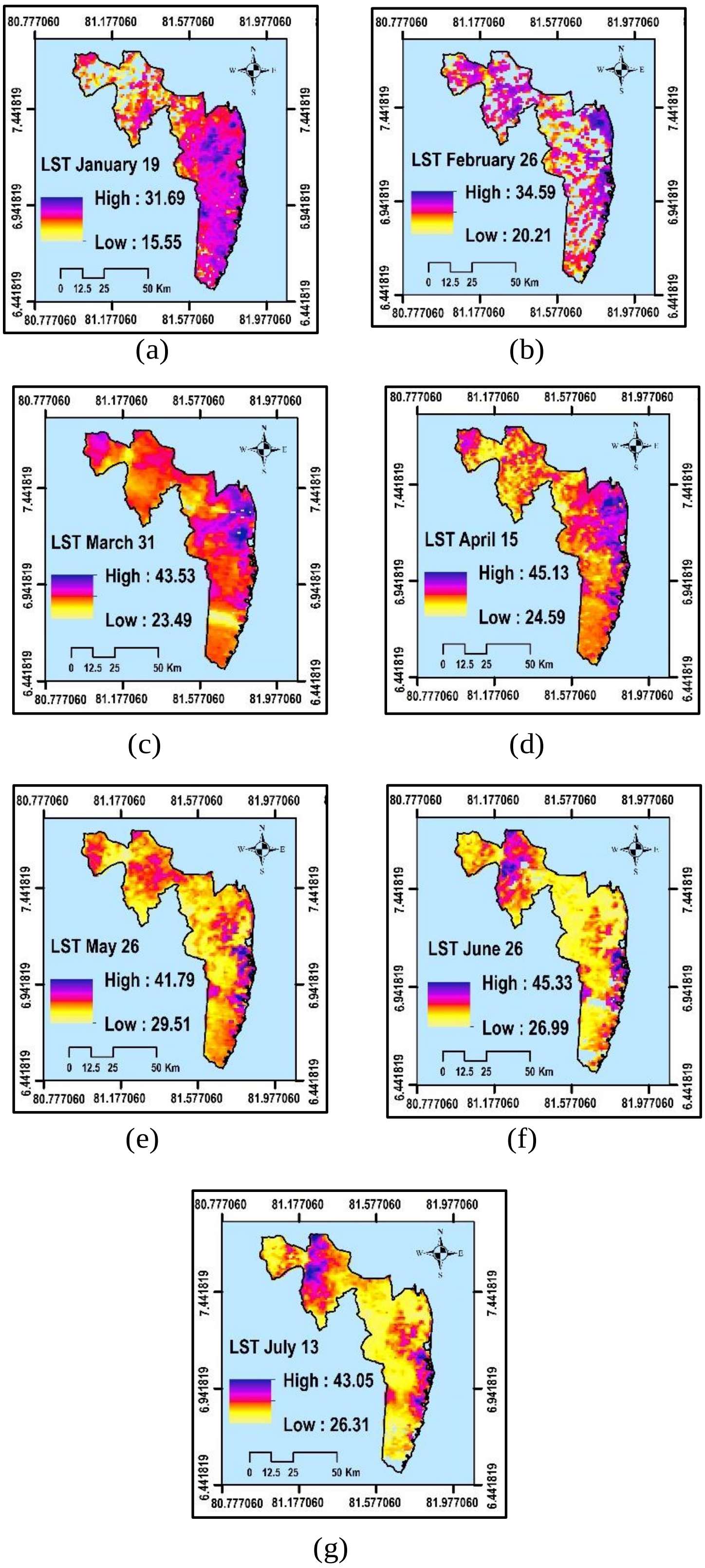

Figure 5: LST (a) 19 January, (b) 26 February, (c) 31 March, (d) 15 April, (e) 16 May, (f) 26 June and (g) 13 July in 2023.

Upon conducting zonal statistics using ArcGIS to analyze the fundamental descriptive connections between LST and various LULC, the outcomes reveal distinct patterns. Significantly, the paddy cultivation zone displays the highest peak in Land Surface Temperature (LST), with readings of 33.31 °C on February 26, 43.34 °C on March 31, 45.13 °C on April 15, 41.79 °C on May 26, 45.33 °C on June 26, and 41.27 °C on July 13 (as shown in Table 3), attributed to the prolonged dry conditions leading to elevated LST. Following this, Hoemgrden, water bodies, non-agriculture, and other land zones exhibit LST readings of 31.47 °C, 31.01 °C, 31.69 °C and 30.49 °C respectively whereas forest at 30.49 °C and wetland at 29.41 °C respectively in January. Similarly, on 26 February and 31 March, the maximum LST gradually increased. However, it was at peak level on 15 April, 26 June and 13 July. The mean lowest LST on specific days within the study area was consistently higher than 33.0 °C.

Table 2: LST Day 1km

Days	LST_Day_1km																				
	Jan			Feb			Mar			Apr			May			June			July		
	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min
1										41.2	31.3	22.6	35.2	30.4	13.5	37.3	27.2	22.3	35.0	31.0	26.7
2	31.1	26.3	17.7							33.9	28.7	19.4				30.8	28.1	22.4			
3	26.9	24.4	21.1					27.6		43.9	32.0	21.8									
4	28.5	26.2	21.6	30.0	25.4	20.8				36.5	30.7	20.3				38.6	31.0	20.6	25.6	25.7	25.6
5	29.6	26.3	20.2	29.1	25.9	19.4	30.8	26.3	17.9	42.9	32.8	25.9				32.6	27.9	21.3			
6							28.5	27.2	26.3	40.6	29.9	21.8				29.7	25.5	20.5			
7	29.5	25.3	15.0	30.0	27.3	23.3	29.1	27.4	22.2	34.5	29.2	23.0				41.1	33.2	28.8			
8				27.1	23.7	16.0	32.8	28.0	21.8	34.0	29.6	23.8	41.2	37.3	27.3				43.5	32.6	23.8
9	27.9	24.6	16.7	32.3	27.7	13.3										42.1	32.4	25.3	38.0	23.2	11.5
10	27.7	24.6	20.2	28.0	25.2	19.8				42.3	32.0	22.7				36.5	31.2	26.9			
11	27.8	24.9	17.5	31.1	29.1	27.7	30.7	25.4	11.0	33.1	28.6	24.4	31.3	27.5	24.0	39.3	32.6	29.2			
12	27.3	20.4	9.1	32.1	27.9	21.1	28.9	27.1	25.4	34.4	29.8	23.1	31.1	27.0	12.9	41.4	32.4	22.1	37.2	30.3	9.1
13							29.9	26.4	21.8	36.9	30.8	22.3	37.2	26.0	5.9	42.5	30.7	21.0	43.1	32.9	26.3
14	31.9	27.6	15.4	33.2	28.4	21.4	25.9	25.7	24.7	28.5	26.0	23.7	31.4	27.8	24.4	31.8	28.9	25.7			
15				28.2	25.4	21.3	33.7	29.0	22.0	45.1	33.6	24.6				39.1	38.8	37.9	44.3	33.7	19.8
16		20.5		32.0	28.4	23.5				32.2	29.0	23.6	36.1	30.9	23.5	38.7	32.6	27.7	40.5	33.0	27.5
17				31.5	26.5	21.4	35.9	30.4	23.0	44.0	34.9	29.4	31.1	27.6	23.2				38.8	31.2	20.4
18	24.2	23.1	19.6	26.4	25.6	23.8	31.8	26.9	22.4	36.8	30.6	24.0	32.9	29.4	24.7	42.7	30.0	22.2	42.7	33.7	22.4
19	31.6	27.0	20.4	25.1	25.1	25.1	31.0	28.5	24.1	35.3	30.5	24.2	34.0	30.5	25.5	39.8	30.5	16.5	48.3	30.8	22.8
20	26.4	25.7	24.9				28.4	26.0	23.6	42.1	33.4	23.8	40.5	29.5	21.3				40.7	33.0	24.8
21													37.2	30.9	23.9	38.8	31.1	23.0	39.8	30.5	18.9
22				29.2	24.9	13.8	38.0	30.5	17.1	35.0	29.8	26.0	30.0	27.7	23.6	29.2	23.4	14.9	39.7	29.5	19.2
23	28.8	25.1	21.9	27.9	22.8	14.4	38.7	32.8	21.2	38.7	36.2	33.3	38.4	31.7	25.8	31.3	27.7	18.7	39.4	31.2	22.2
24	25.5	24.3	19.5	32.2	28.0	22.3	33.3	28.9	19.0	35.1	30.8	23.0	37.2	30.9	26.2	38.2	28.7	23.2			
25							34.8	28.6	18.0	38.3	30.9	21.1	36.7	31.9	28.8	38.7	28.9	16.7	31.6	25.7	19.6
26				33.8	27.8	20.2	32.0	27.0	24.0	27.9	23.9	20.7	41.8	33.4	29.7	45.3	33.1	26.0			
27				25.0	23.3	21.7	40.6	31.4	22.3							36.2	30.6	25.3	44.3	33.7	14.8
28	28.8	26.3	19.5							34.7	28.8	20.4	39.9	32.8	28.0	41.7	33.0	25.9	41.1	32.9	27.8
29	28.1	26.7	19.4				35.8	29.5	17.9				32.1	28.5	23.5	39.5	31.6	25.3	40.3	33.4	28.4
30	35.6	28.9	21.9				34.9	28.1	22.5	34.6	29.9	24.6	37.1	31.2	26.8	41.1	32.0	26.6	38.5	31.0	21.5
31							43.5	32.8	23.5				37.9	31.1	24.4						

Table 3: LST Value in Different Land Use Classes

19 January 2023 LST (^{0C})				
Zone Code	**Min**	**Max**	**Range**	**Mean**
1	21.55	31.47	9.92	26.99
2	21.87	30.79	8.92	27.36
3	20.43	31.01	10.58	26.41
4	24.89	31.69	6.8	28.72
5	23.23	30.49	7.26	26.59
6	15.55	30.49	14.94	26.83
7	26.17	29.41	3.24	27.73
26 February 2023 LST (^{0C})				
Zone Code	**Min**	**Max**	**Range**	**Mean**
1	22.29	32.63	10.34	28.41
2	21.89	33.31	11.42	28.40
3	21.77	31.81	10.04	26.64
4	22.21	34.59	12.38	29.17
5	21.69	32.91	11.22	28.19
6	20.21	31.63	11.42	27.31
7	23.23	31.59	8.36	29.32
31 March 2023 LST (^{0C})				
Zone Code	**Min**	**Max**	**Range**	**Mean**
1	29.57	39.89	10.32	33.41
2	26.75	43.53	16.78	34.59
3	25.89	38.91	13.02	32.08
4	30.79	38.75	7.96	34.51
5	28.37	39.67	11.3	32.55
6	23.49	37.05	13.56	31.76
7	31.55	37.87	6.32	33.95
15 April 2023 LST (^{0C})				
Zone Code	**Min**	**Max**	**Range**	**Mean**
1	26.65	43.67	17.02	33.89
2	27.77	45.13	17.36	35.33
3	27.73	39.17	11.44	33.00
4	28.85	40.79	11.94	35.54
5	25.29	43.87	18.58	33.24
6	24.59	39.11	14.52	32.64
7	30.05	38.23	8.18	35.10
26 May 2023 LST (^{0C})				
Zone Code	**Min**	**Max**	**Range**	**Mean**
1	31.37	36.93	5.56	33.51
2	30.55	41.79	11.24	33.96
3	30.09	39.97	9.88	32.84
4	31.91	37.37	5.46	34.23
5	29.51	37.83	8.32	33.33
6	29.55	39.99	10.44	33.14
7	31.53	38.35	6.82	34.78
26 May 2023 LST (^{0C})				
Zone Code	**Min**	**Max**	**Range**	**Mean**
1	29.09	42.61	13.52	32.84

2	28.49	45.33	16.84	33.08
3	29.79	40.17	10.38	32.71
4	29.77	36.99	7.22	33.53
5	27.93	42.35	14.42	33.38
6	26.99	42.19	15.2	33.15
7	30.13	38.97	8.84	33.97
13 July 2023 LST (^{0C})				
Zone Code	**Min**	**Max**	**Range**	**Mean**
1	29.71	40.41	10.7	32.54
2	29.29	41.27	11.98	32.97
3	29.67	39.99	10.32	32.61
4	30.69	36.93	6.24	33.16
5	28.65	41.75	13.1	33.20
6	26.31	42.35	16.04	32.81
7	30.17	37.23	7.06	33.55

(Zone Code: 1 - Homegarden, 2 - Agricultural land, 3 - Water bodies, 4 - Non-agricultural Land, 5 - Other Land, 6 - Forest and 7 - Wetland)

The decrease in vegetation growth, resulting in a barren soil surface, was seen as a contributing factor to the LST during the aforementioned dates. Conversely, an analysis of mean LST values revealed that non-agricultural zones are dominant, followed by areas with minimal vegetation presence (e.g., built-up, industrial, commercial, public, private, and transportation areas). The most significant temperature variation between LST and LULC was identified within forests on 19 January, 26 February, 31 March, 15 April, 26 May, 26 June, and 13 July. This notable increase in LST was attributed to forest vegetation drying and openings occurring on these specific days.

The mean LST values for these LULCs on specific days of each month reveal that forests and wetlands mitigate the LST impact. Conversely, an analysis of the combined mean and maximum LST values led to the observation that vegetated areas amidst other LULC alleviate the LST influence. As a result, vegetated regions contribute to lowering LST during the hottest days of the month.

3. Conclusion

The comprehensive analysis of LST data spanning from January to July 2023 has illuminated significant patterns and fluctuations in day temperatures. Incorporating LULC data into the study provided insights into the intricate interplay between LST and various LULC types. Particularly, the results depicted a distinct shift in LST, with elevated temperatures observed from the end of March through July. The pinnacle of temperature, surpassing 40°C, was reached in April and May. Conversely, June and July maintained consistently high LST values.

A noteworthy finding was the amplification of temperature ranges during the warmer months, particularly from April to July. Vegetation-rich areas exhibited lower LST values compared to urbanized and less vegetated zones. The study highlighted localized zones with intensified LSTs, primarily concentrated within densely urban and sparsely vegetated regions.

Employing zonal statistics in ArcGIS enabled the identification of key relationships between LST and specific LULC types. Notably, paddy-cultivated regions exhibited the highest LST peaks, followed by different LULC. The study elucidated the role of reduced vegetation in contributing to elevated LST, with forests displaying significant temperature spikes on specific days.

Overall, the analysis underscores the importance of vegetation in mitigating LST impact, particularly during the hottest days of each month. The research provides valuable insights for urban planning, land management, and climate resilience strategies, emphasizing the crucial role of vegetation in counteracting the urban heat island effect and promoting temperature moderation.

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ESTIMATION OF ANNUAL ENERGY PRODUCTION AND DEVICE PARAMETER OPTIMISATION IN SRI LANKAN WAVE CLIMATIC CONDITIONS

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Abstract: Sri Lanka is a country struggling with energy security. Being an island surrounded by sea, achieving a sustainable energy mix with marine renewable energy development is possible. The latest study conducted with international recommended standards for the Sri Lankan wave energy resource has shown that the marine environment around Sri Lanka has moderate wave characteristics with small frequency bandwidth and narrow directionality of sea states, which provide opportunities to wave energy converter developers. This study establishes a foundation for estimating the annual energy production, offering a sample analysis that can serve as a reference for developers aiming to assess the Mean Annual Energy Production (MAEP) at a specific location along the southern coast of Sri Lanka, considering the utilization of an appropriate wave energy converter (WEC) system. Initially, a wave energy resource assessment, which characterizes the wave climate and energy potential, was conducted at a selected site with international specifications. Afterward, a 150 kW heaving point absorber type WEC was modeled based on the results of the energy resource assessment. The power capture was optimized by choosing the optimum values for the buoy mass and choosing the shape according to the dominant sea state in the selected site. The power absorption was optimized by tuning the coefficients of the spring-mass damper. Furthermore, a latching control was implemented to maximize the available energy harvest. Finally, the MAEP was estimated by computing the energy production for 120 sea states related to Sri Lankan climatic conditions. This research concludes that Sri Lanka's southern coastal region can provide wave energy with a high-capacity factor, which is a positive sign for potential developers.

Keywords: Wave energy; Mean Annual Energy Production; Wave Energy Converter; WEC optimization

1. Introduction

Due to the consequences of non-renewables on the environment and climate change, there is growing interest in using renewable energy worldwide. Environmental effects, energy security, the depletion of fossil fuels, and other issues can be overcome by using renewable energy sources. Sri Lankan energy supply is highly dependent on importing coal and other fuel oils. Being an island surrounded by sea, it is crucial, and achieving a sustainable energy mix with the development of marine renewable energy is possible.

Although wave energy has not made a breakthrough in the energy world, research has been conducted for years. Wave energy will be economical in the future and certain since its energy density is five times that of wind and more predictable than wind energy(Lopez et al. 2013). Several wave energy companies have expressed their inclination to deploy Wave Energy Converters (WECs) in the waters surrounding Sri Lanka. However, the absence of dependable datasets for estimating Mean Annual Energy Production (MAEP), coupled with significant uncertainties, is one of the critical drawbacks that hinders the realization of these intentions. The management of uncertainty holds substantial sway as a critical determinant before committing investments into projects of this nature(Lokuliyana et al. 2023). This endeavor aims to tackle this challenge by providing a solution for accurate MAEP estimation through an appropriate application of Wave Energy Converter (WEC).

2. Wave climate

Wave energy projects initiate with a wave energy resource assessment that characterizes the wave climate and energy potential. According to Herbich John B. and Walters (1987), wave climate is defined as the distribution of wave height, period, and direction averaged over a period for a particular location. The wave climate includes all the environmental aspects that influence the power performance of WEC. It consists of data sets such as water depth, wave currents' strength, and wind effects. These parameters change with time. Therefore, the parameters are represented in a way that varies with time. This representation is generally used to define any sea state. There are three ways of representing wave climate; namely Scatter table, Abridged and extensive. In this research, the scatter table method is used. A detailed study on the resource assessment for the Sri Lankan region was conducted by (Lokuliyana et al. 2020), laying a solid foundation for a more in-depth exploration of the wave energy in the vicinity of Sri Lanka.

2.1 Mathematical Modeling of WEC

The development of WECs is characterized by the ideas and concepts for how to utilize the wave energy resource. The primary device categorization is done as the terminator, attenuator, and point absorbers. If the horizontal size of the device is much smaller than the typical wavelength, the WEC is called a point absorber; otherwise, it is called a terminator or attenuator, depending on whether it is aligned normally or parallel to the prevailing wave direction. In this research, a WEC is modeled as a single body point absorber with a single degree of freedom along the vertical axis (heave mode), as this accounts for most of the movement(Davidson and Ringwood 2017). The hydrodynamics of the WEC is determined by the sum of hydrodynamic forces acting on the body FH(t) and the Power Takeoff (PTO)system, FPTO(t);

$$F_H(t) + F_{PTO} = m\ddot{z}(t) \tag{1}$$

Where m is the mass of the apparently and $\ddot{z}(t)$ represents the acceleration along heave mode(Cargo et al. 2012). Hydrodynamic forces can be further decomposed into,

$$parentF_H(t) = F_e(t) + F_{rad}(t) + F_{hs}(t) \tag{2}$$

Where $F_e(t)$ represents the excitation force, the force exerted by the incident wave. The radiation force, $F_{rad}(t)$ is the force produced by the motion of the body, creating waves on an otherwise calm sea. $F_{hs}(t)$ is the force linearized hydrostatic force caused by buoyancy.

It can be assumed that the excitation force is proportional to the incident wave amplitude and given by,

$$F_{hs}(t) = \Gamma(\omega)\frac{H}{2}\sin(\omega t) \tag{3}$$

Where $\Gamma(\omega)$is the excitation force coefficient, which depends on the body shape and the incident wave frequency(Falnes and Kurniawan 2020a). H is wave height. Radiation force is modeled as the combination of terms with the buoy's acceleration and velocity named added mass and radiation damping, respectively.

$$F_{rad}(t) = -A(\omega)\ddot{z}(t) - B(\omega)\dot{z}(t) \tag{4}$$

The coefficients $-A(\omega)$ and $B(\omega)$ are added mass and radiation damping coefficients, respectively. The coefficients depend on the buoy shape and the incident wave frequency (Falnes and Kurniawan 2020b). The hydrostatic force is given by,

$$F_{hs}(t) = -\rho g S z(t) \tag{5}$$

Where S is the wetted surface area of the buoy. F_{PTO} Equation (1) represents the forces applied on the buoy by the PTO and the mooring system. In this study, the mooring effect is assumed to be negligible compared to the force by the PTO unit.

$$F_{PTO} = -C\dot{z}(t) - kz(t) \tag{6}$$

Where C is the damping coefficient, and k is the spring constant. The equation (1) can be rewritten as

$$\left(m + A(\omega)\right)\ddot{z}(t) + (B(\omega) + C)\dot{z}(t) + (\rho g S + k)z(t) = F_e(t) \tag{7}$$

2.1.1 Frequency domain analysis

Solving the equation (7) in the frequency domain is straightforward to determine the maximum energy absorption. Taking the Laplace transformation, the equation (7), neglecting the physical spring (k).

$$\frac{X(s)}{F_e(s)} = \frac{1}{(m+A)s^2 + (B+C)s + (\rho g S)} \tag{8}$$

Transforming into Frequency domain,

$$X(j\omega) = \frac{F_e(j\omega)}{-\omega^2(m+A) + j\omega(B+C) + \rho g S} \tag{9}$$

Equation (8) can be rewritten in terms of velocity,

$$U(j\omega) = \frac{F_e(j\omega)}{j\omega(m+A) + (B+C) + (\frac{\rho g S}{j\omega})} \tag{10}$$

The average useful power absorbed is given by,

$$P_{abs} = \frac{1}{2}C|U(j\omega)|^2 \tag{11}$$

Substituting from (2.9)

$$P_{abs} = \frac{1}{2}C\frac{F_e(j\omega)^2}{(B+C)^2 + (\omega(m+A) - \left(\frac{\rho g S}{j\omega}\right))^2} \tag{12}$$

2.1.2 Time domain analysis

Due to the practical limitations, analysis of realistic systems should be conducted in the time domain. Cummins(Cummins 2007) developed an approach that has been widely used in the modeling of WECs. With this approach, the equation (6) takes the form of

$$(m + A_\infty)\ddot{z}(t) + \int_{-\infty}^{t} L(t-\tau)\,\dot{z}d\tau + (\rho g S)z(t) = F_e(t) + F_{PTO}(z, \dot{z}, t) \tag{13}$$

Where A_∞ is the added mass at $\omega = \infty$. *L(t)* is a function representing the memory effect of the radiation force, which depends on the latest incidences on the buoy.

2.2 Power Optimization

The ability of a body to absorb the energy from the waves depends on its hydrodynamic design. In general, it is said that 'A good wave absorber must be a good wave maker'(Falnes and Budal 1982). As aforementioned, the shape and size of the buoy plays a significant role in power extraction. Budal et al. (1980) were able to formulate power absorption bound for floating WECs that oscillate in heave. Even within the bounds, for an unconstrained point absorber to achieve optimum energy absorption in a regular sinusoidal wave, the following two conditions should be fulfilled.

1. The velocity of the oscillator is in phase with the dynamic pressure of the incoming wave.
2. The amplitude of the motion of the oscillator at the resonance condition needs to be adjusted so that the amplitude of the incident wave is twice the amplitude of the radiated wave from the oscillator.

It is known that the maximum amplitude (hence, the velocity) occurs when an object is in resonance with its natural frequency. The same theory applied. The resonant frequency of the buoy can be obtained by

$$\omega_0 = \sqrt{\frac{\rho g S}{m + A(\omega_0)}} \tag{12}$$

Where $A(\omega_0)$ is the added mass at the natural frequency, and the hydrostatic force acts as the spring effect. In addition, from equation (9) and (12), it can be derived that the maximum P_{abs} is achieved when $C_{PTO} = B(\omega)$ and $K_{PTO} = \omega^2\big(m + A(\omega)\big) - \rho g S$

However, PTO stiffness K_{PTO} can take negative values for the range. $\rho g S > \omega^2\big(m + A(\omega)\big)$. A positive K_{PTO} can be achieved easily, while implementing a negative stiffness requires power flow through PTO, which is hard to achieve in practice. Therefore, in this case, the K_{PTO} is neglected (sub- optimal condition)(Ringwood et al. 2014).

C_{PTO} can be adjusted based on sea state or real-time wave-by-wave optimization, depending on the control method. In terms of power production, the latter technique is the most optimal reactive control. However, it requires an accurate plant model and a future comprehension of the wave excitation forces. Therefore, for simplicity, a fixed damping is used that has been optimized for the most dominant sea state.

3. Methodology

Initially, a wave energy resource assessment, which characterizes the wave climate and energy potential, was conducted at a selected site with international specifications. The wave climate includes all the environmental aspects that influence the power performance of a Wave Energy Converter (WEC)(Folley 2017). It is known that the Sri Lankan southern coast contains higher wave energy than the other coastal areas on the island(Chamara and Vithana 2019). Therefore, a site was chosen from the southern coast as the point of interest to estimate Mean Annual Energy Production (MAEP) near GPS location 6.1105 N, 81.0788 E. Another significant reason for choosing that specific point of interest was that the available dataset was from a previously deployed wave-measuring buoy.

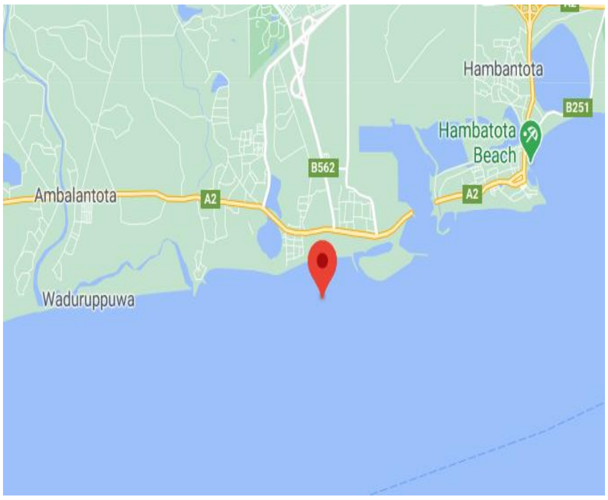

Figure 1: Selected site for MAEP calculation.

3.1 Wave energy resource assessment

A third-generation wave propagation model, SWAN was used to model the waves. The computational spatial grid was generated using the 'Triangle mesh generator.' A graphical MATLAB interface known as 'BatTri' was used to generate an accurate grid where the bathymetry changes rapidly.

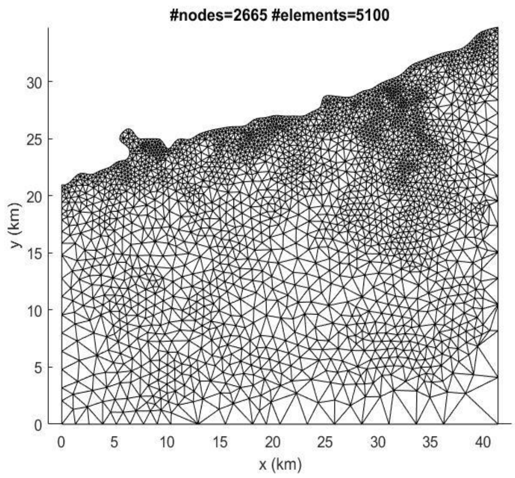

Figure 2: Unstructured grid.

For the model constructions, bathymetry, wind, and spectrum data were used as input grids for the SWAN wave propagation model. Bathymetry data was obtained by the General Bathymetric Chart of Oceans (GEBCO) while the wind data and 2D spectrum data were obtained from the European Centre for Medium Range Weather Forecasts (ECMWF). Other input data was acquired by the previously deployed wave buoy. The other unknown parameters, such as white capping and bottom friction, were changed as wave parameters inside SWAN. Significant wave height and the energy period were obtained as the SWAN output grid.

3.2 Modelling of the device

A 150kW spherical-shaped heaving point absorber type WEC was modeled based on the wave energy resource assessment results.

Table 1: Parameters acquired from the wave energy resource assessment for WEC modeling.

Parameter	Notation	Value
Energy period	T_e	9 s
Significant wave height	H_s	0.7 m
Sea depth	J	45 m
Energy density	ρ	27.4kW/m

Table 2: Dimensions of the modeled WEC

Parameter	Value
Volume	419 m^3
External diameter	9.28 m
Internal diameter	7.82 m
Buoy mass	215 000 kg

The spherical buoy was modeled using SolidWorks and meshed using Ansys Meshing. WEC was then simulated in both regular waves to approximate the frequency domain hydrodynamics of the WEC by Finite Element Method (FEM) using Ansys AQWA commercial software. Ansys code is based on the Boundary Element Method (BEM) and the linear potential theory, which is a suitable approximation for modelling point absorbers.

Hydrodynamics was then simulated in both regular waves and irregular waves with different wave heights and wave periods in the time domain using WEC-Sim, an open-source wave energy converter simulation tool developed in MATLAB and Simulink tool.

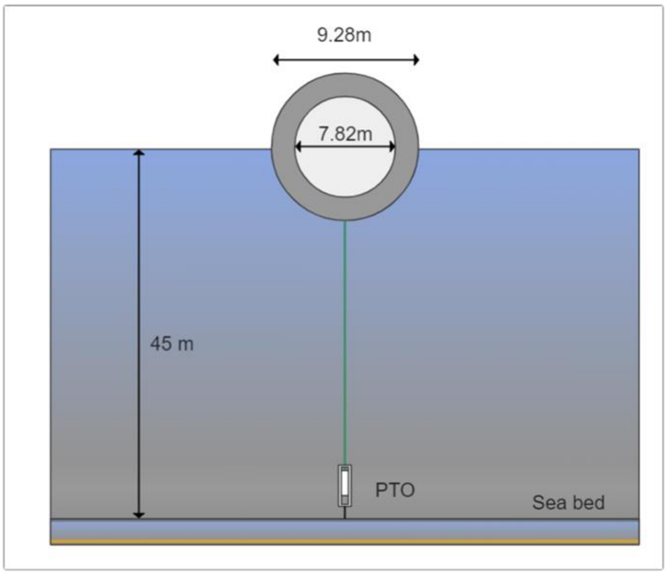

Figure 3: Schematic diagram of the modeled buoy.

4. Performance Optimization

The power capture was optimized by choosing the optimum values for buoy mass and choosing the shape according to the dominant sea state in the selected site. A sea state is characterized by statistics, including the wave height, wave period, and spectrum. However, the power absorption must be optimized by tuning the Power Take Off (PTO) system. The PTO can be approximated as a spring-mass damping system. A mathematical model was formulated to optimize the power absorption from the PTO system. The power absorption could be optimized by changing the damping constant and the stiffness value of the PTO system.

Initially, the WEC was optimized for each sea state, and the power matrix was obtained. However, a forecast of the incoming waves is required to implement such an optimization strategy. Furthermore, there is only a limited time frame to adjust the damping value according to the incoming wave, which is impractical for implementation without a high-tech control. It is also not cost-effective to implement such a high-tech application.

Considering these reasons, WEC was optimized for the most dominant wave period (implemented with a fixed damping constant corresponding to the dominant wave period). Furthermore, a latching control(Giorgi and Ringwood 2016) was implemented to maximize the available energy harvest. The latching control algorithm takes an iterative approach. This iteration process was necessary since the external forces vary with each iteration due to the variation of applied PTO forces.

5. Results and Discussion

Characterization of the wave climate and the wave energy potential in terms of sea states is shown in Figure 4. The simulations were conducted for 120 sea states.

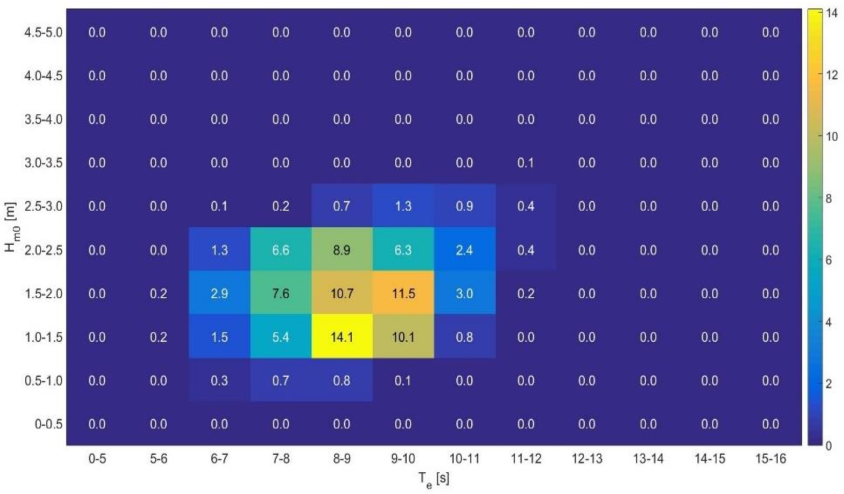

Figure 4: Representation of wave climate as a scatter table.

The percentage of occurrence was considered when designing the WEC since the results from the wave energy resource assessment are significant in maximizing the capacity factor of WEC which should be maximal for the range of wave height and the period providing the bulk of the energy.

The power performance of a WEC can be expressed as a ratio between the absorbed energy from the PTO and the available energy at the sea. This ratio is known as the Capture Width Ratio (CWR). Variation of CWR of the WEC with the significant wave height is illustrated in Figure 5.

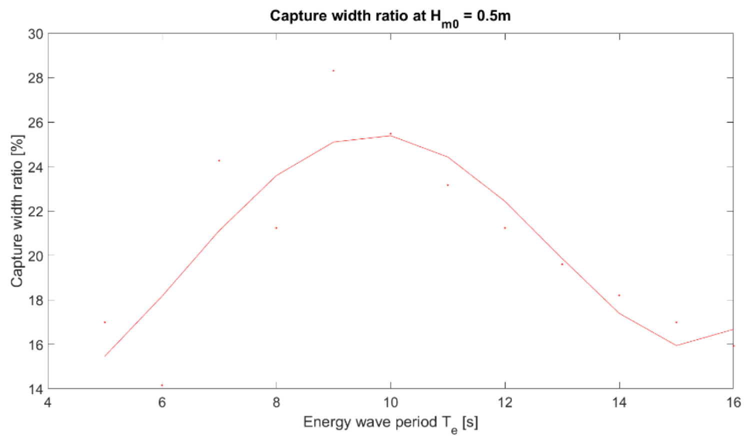

Figure 5: Capture Width Ratio of the WEC in irregular waves as a function of energy wave period at H_s=0.5m.

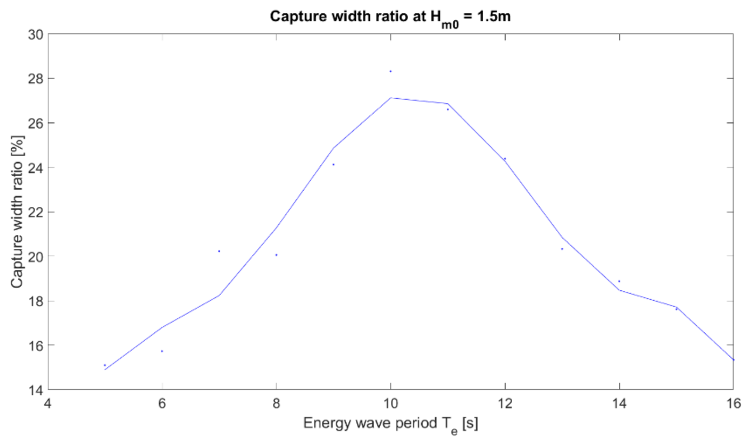

Figure 6: Capture Width Ratio of the WEC in irregular waves as a function of energy wave period at Hs=1.5m.

The power performance of the WEC after optimizing the WEC for the most dominant sea state in regular waves (optimal reactive control) is shown in Figure 7.

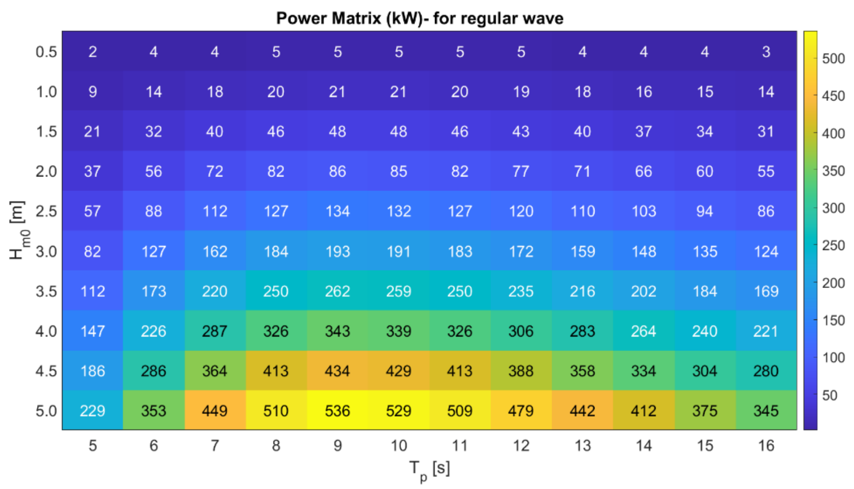

Figure 7: Variation of Power Performance of WEC in regular waves with H_s and T_p.

Afterwards, WEC was simulated in irregular waves (Jon Swap spectrum) and the power was constrained to 150kW.

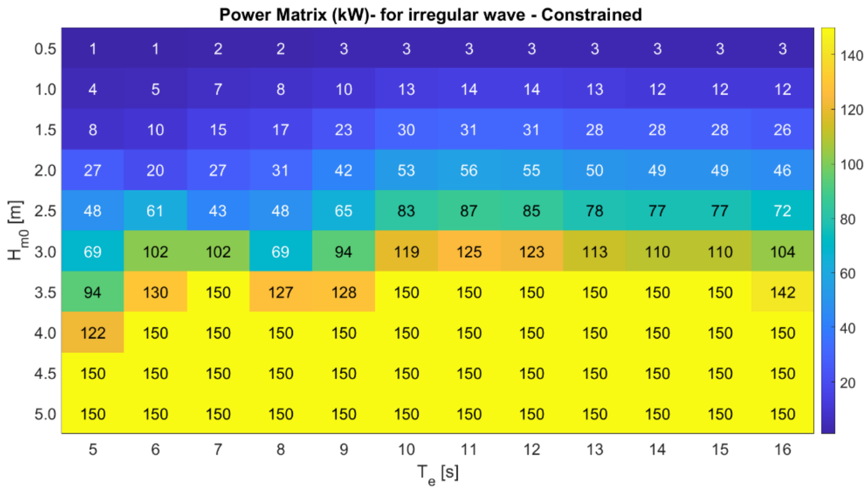

Figure 8: Variation of Power Performance of WEC in irregular waves with H_s and T_e.

Computing the energy production for 120 sea states with the model for the period from August 2013 to April 2014 is summarized in Table 3.

Table 3: Annual mean power calculated with Scatter table - Power matrix method for the period from August 2013 to April 2014.

Parameter	**Value**
Nominal Power	150 kW
Average power	82kW
Capacity factor	55%
MAP	716 MWh/year

The present study modeled and simulated a point absorber-type wave energy device of 150 kW. The current study estimates that 716 MWh of energy can be absorbed from the buoy annually with an average of 82 kW with a capacity factor of 55%.

6. Conclusions

It can be concluded that with further study and improvement of this research, it can be proven that the implementation of a WEC in Sri Lanka could be a profitable investment for WEC developers. The capacity factor can be further increased by having a compact array of smaller buoys instead of one. The 55% capacity factor is remarkably high for renewable energy resources. Therefore, Sri Lanka's southern coastal region can provide wave energy with a high-capacity factor, which is a positive sign for potential developers. This is also a positive sign of balancing the renewable energy supply through a proper energy mix according to the 100% renewable energy target in 2050.

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CLIMATE CHANGE AND PADDY CULTIVATION OF SRI LANKA

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Abstract: Anomalous climate change is a widespread topic currently emphasized in most of the studies in the world due to its impacts in many ways. Being an island, the effect of El Nino and La Nina phenomenon and the monsoons have resulted in the occurrence of a range of climate variations in Sri Lanka resulting in extreme weather conditions including severe floods and droughts. On the other hand, Sri Lanka is a country where agriculture is one of the dominant industries with rice being the staple food. Therefore, in the agricultural sector, paddy cultivation plays a crucial role in providing rice on the requirement to the nation. There are two distinct agricultural seasons; "Yala" (April to September) and "Maha" (October to March) considering the annual rainfall in the country, and, paddy growing takes place in different zones of the country which have mainly divided as dry zone, wet zone and intermediate zone. But, the extreme climate events have directly influenced paddy cultivation in Sri Lanka challenging the economy of the country. This study aims to suggest adaptation strategies to overcome the challenges due to varying climates, on paddy cultivation during the above-mentioned agricultural seasons and in the different zones in Sri Lanka. The methodology comprises a literature survey on published works that addressed the issues of climate change and paddy cultivation and have presented the adaptation strategies followed which apply to Sri Lanka to minimize the negative impacts of climate change on paddy cultivation.

Keywords: Climate change; Monsoons; Paddy cultivation; Economy; Adaptation strategies

1. Introduction

Sri Lanka is an island endowed with the best environmental conditions for agriculture, which is deliberately pursued in the interest of sustainability (Ranathunga et al., 2018). The foundation of the Sri Lankan people's way of life is their long history of agriculture, which dates back more than 2500 years. The country is known as the Pearl of the Indian Ocean because of its consistently moderate climate, optimum rainfall and temperature patterns over the year, extensively extended freshwater network made up of man-built reservoirs, rivers, and other sources of freshwater, and surrounding fertile soil (Ranathunga et al., 2018). 70% of the country's population lives in rural areas and 80% out of them depend on agriculture and natural resources for their livelihood, while these sectors play a significant role in enhancing household food and financial security in Sri Lanka. More than 10% of the GDP, 30% of employment, and 25% of export earnings are accounted for by the industry as a whole (Mahaweli Water Security Investment Program, 2015).

In Sri Lanka, rice is the staple food and therefore paddy is one of the most significant crops, accounting for 34% of all cultivated lands in the country (Senanayake and Premaratne, 2016). Nearly 750,000 hectares of irrigated lands are used to produce more than 80% of the nation's rice. Paddy cultivation is heavily reliant on seasonal precipitation and irrigation water supplies, which historically came from tanks, storage reservoirs, and recently from transfers from dams connected with major river basins (Mahaweli Water Security Investment Program, 2015).

But at the moment, paddy cultivation is made challenged by unfavorable weather circumstances like floods brought on by a lot of rain and ensuing droughts all year long. In general, the data on actual and anticipated changes show that Sri Lanka's climate is undergoing three primary types of changes: a steady increase in temperature, changes in the pattern of rainfall distribution, and an increase in the frequency and severity of extreme weather events (Baba, 2010). By 2050, there will be a 13–23% rise in water demand during the Maha season due to a decrease in average rainfall, an increase in potential evapotranspiration, and a shorter rainy season. The Yala season will see a large increase in the need for irrigation water in the dry and intermediate zones challenging the economy of the country (Ministry of Mahaweli Development and Environment, 2015). On the other hand, floods cause severe damages to the cultivated lands losing millions of tons of upcoming paddy harvest. In recent history, the worst-hit areas in Sri Lanka were in the eastern districts of Ampara, Batticaloa, Polonnaruwa, Trincomalee, and the north-central district of Anuradhapura (Pavithira, 1984).

This study aims to interpret the adaptation strategies that can be involved in paddy cultivation practices to overcome the threats caused due to climate change, through a thorough literature survey.

2. Methodology

To address the above issue, a literature survey was conducted to emphasize the adaptation strategies suggested in similar research studies. Accordingly, published research articles, reports, books, and other sources of information were used relevant to climate and paddy cultivation, based on the research gap identified, Sri Lanka was the study area and solutions were presented suitably.

3. Climate and Climate zones of Sri Lanka

There are numerous sources of rain in Sri Lanka. The majority of the yearly rainfall is caused by convectional and monsoonal rainfall, as well as the production of synoptic weather, particularly in the Bay of Bengal. On average, the island receives 900 millimeters of rain annually in the southeast of the Dry Zone and over 5,500 millimeters in the southwest slopes of the Central Highlands(Filho, 2015). This rainfall can be characterized into four rainfall seasons according to the temporal pattern. The northeastern monsoon (NEM), which produces the precipitation between January and February, and the first inter-monsoon (FIM), which occurs in March to April, generally brings modest precipitation over the nation. The southwestern monsoon (SWM), occurs from May to September, usually records the highest precipitation, where the humid zone experiences heavy rains. Between October and December, the second inter-monsoon (SIM) takes place, and precipitation from SIM typically produces more rain than FIM (De Silva and

Hornberger, 2019). Accordingly, as per the rainfall received due to these monsoons, the country has been split into three distinct climate zones as in Figure 1, the Wet Zone, Intermediate Zone, and Dry Zone. The country's southwest regions, which involve the central hill areas fall under the Wet Zone, where mean annual rainfall is more than 2500 mm, while the northern and eastern regions are covered by the Dry Zone with annual rainfall of under 1750 mm. The intermediate zone is located in between these two zones and gets a mean annual rainfall ranging from 1750 mm to 2500 mm (Ranathunga *et al.*, 2018).

In Sri Lanka, the productivity of the agricultural sector is significantly influenced by the climate. As a result, farming systems and agronomic methods have developed in close coordination with the local climatic conditions throughout the majority of Sri Lanka's agricultural regions. The vast majority of scientific studies have shown general trends in Sri Lanka's climate as; rising temperatures that cause more heat stress and an increase in the frequency and severity of extreme rainfall resulting in anomalies in droughts and floods.

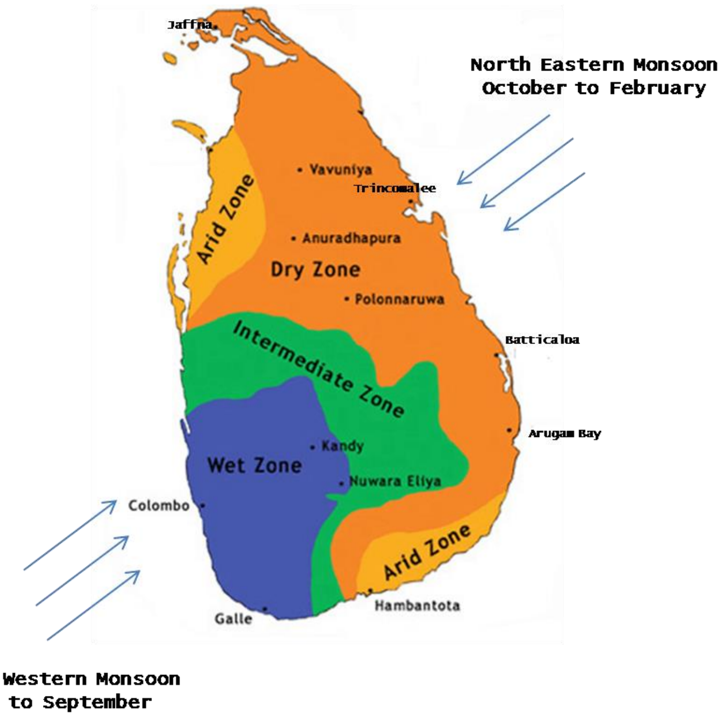

Figure 1 - Climate zones and major monsoons experienced by Sri Lanka
Source : (Magnificent Sri Lanka, 2020).

4. Paddy cultivation in Sri Lanka

There are two primary crop seasons within the country 'Yala' and 'Maha'. Maha is the primary growing season, lasting from October to March, while Yala is the secondary growing season, lasting from April to September (Chandrasiri et al., 2023). Maha season is fed by the second inter-monsoon and the north-east monsoon rains, while, Yala season is fed by the first inter-monsoon rains and the southwest monsoon.

With a total of 4.98 million tonnes, including 3 million tonnes in the Maha season and 1.98 million tonnes in the Yala season, Sri Lanka's paddy production peaked in 2020. This production was 85 percent more than the production in 2000. During the years 2000 to 2020, the average paddy yield was 4.23 tonnes/ha, resulting in an annual production of 3.71 million tonnes (Salman, Ahmad, and Giusti, 2022).

Paddy cultivation is more susceptible to climate factors such as evapotranspiration, temperature, and rainfall. Therefore, alterations in these characteristics would have a significant effect on the crop's development and output (Dananjaya, Shantha, and Patabendi, 2022).

17% of the country's total paddy crop was produced in the Anuradhapura District. During the 2019/2020 Maha season, the Kurunegala, Ampara, Polonnaruwa, Batticaloa, and Hambantota Districts were anticipated to contribute 12%, 11%, 10%, 6%, and 6%, respectively, to the nation's total paddy production. In Sri Lanka, a variety of seeds with long-grain white, short-grain white, long-grain red, and short-grain red types are sown (Department of Census and Statistics Sri Lanka, 2020). Variations in how much is sown, the amount harvested, and the average yield, paddy production varies each year and season (Razmy and Ahmed, 2019).

5. Impact of climate change on paddy cultivation in Sri Lanka

A plant that is extremely sensitive to climate factors is rice. In rice cultivation, there are three main growth stages: vegetative, reproductive, and ripening, and each stage has a particular temperature requirement. Literature provides sufficient case studies where climate directly impacts on paddy cultivation and yield.

The numerous reservoirs in the dry zone eventually dry up if the amount of rainfall decreases. It results in immediate effects on the agricultural sector, particularly during the "Yala" paddy growing season (which is associated with the southwest monsoon), where the effective rainy season is from May to August (de Silva and Sonnadara, 2016). Harvesting intensities of paddy are often limited to around 100 to 130% since the vast majority (70%) of irrigated fields are situated in the dry zone, where water supply is a key barrier throughout the Yala season. On the other hand, due to greater water availability in the wet zone, cropping intensities are often limited to 150 to 180% in the wet zone (Mahaweli Water Security Investment Program, 2015). Due to the north-east monsoon season, the heaviest flooding occurred in 2011 in the eastern province in the second and first weeks of January, with Batticaloa receiving 312.2 mm, recording the third-highest amount of rainfall in a single day in the city's history. It mostly affected the production of rice in the Batticaloa district and had an indirect and direct impact on the yield and socioeconomic status of paddy farmers. The findings show that 44,179 paddy farmers have been significantly affected by the flood, which has reduced rice production by 159,500 metric tons compared to 2010 (Pavithira, 1984). Also, it has been identified that climate change-related pest and disease issues include the emergence of new illnesses and insect infestations among paddy crops (Zubair *et al.*, 2015). Accordingly, it is noted that immediate solutions are needed to address the issues caused due to climate change in paddy cultivation.

6. Adaptation strategies to overcome the challenges of Paddy Cultivation due to climate change

Strategic approaches for adaptation in Sri Lanka would be strengthened by systematic crop comparison programs under various agro-ecological regions of the country through farmer participation programs. Strengthening crop germplasm collection programs run by the Department of Agriculture with a focus on climate change, and facilitating access to bringing in new genetic materials through intergovernmental programs will positively boost food production (Filho, 2015).

The National Adaptation Plan on Climate Change included several recommendations for strategies to lessen adverse effects on agriculture due to climate change. It includes the following key points in brief;

- Strongly encourage the use of effective water management techniques in all types of agriculture.
- Create and introduce rice types that are drought and pest-tolerant.

- Breeds of livestock and poultry that can withstand heat stress and disease should be encouraged.
- Promote agricultural calendar modification in response to climate predictions.
- Create a reliable early warning system for monitoring the climate, performing climate analysis, and informing farmers about the climate.
- Increase preparedness for climate change research and creation of livestock breeds and agricultural variants that are heat- and drought-resistant.
- For vulnerable watershed areas, create and put into action comprehensive watershed management plans.
- Create plans for disaster risk management and identify and map regions that are susceptible to drought and flood hazards.
- Create logical intra- and trans-basin methods to utilize recurring water surpluses in storage facilities.
  (Ministry of Mahaweli Development and Environment, 2015)

The International Rice Research Institute (IRRI) is working to create rice varieties that can endure the more frequent and severe weather that is predicted to come with climate change. This includes extreme weather conditions such as excessive drought, flood, heat, and cold. These improved varieties of "climate change-ready rice" are demonstrating significant, beneficial impacts in the lives of poor farmers, together with improved crop management, correct use of technology through extension work, and assistance from national institutions.

Popular high-yielding rice cultivars including IR64, Swarna, and Vandna are being worked on by IRRI to develop drought resistance. Several landraces with tolerance to various types of flooding have evolved throughout Asia, although the majority of high-yielding rice cultivars suffer significant losses as a result of floods. For instance, deep-water rice types can stretch quickly to survive, whereas most high-yielding modern varieties are unable to elongate sufficiently. The rice plants expend so much energy attempting to escape floods that continue for more than a few days that they are unable to recuperate. Currently, rice cultivars with better robustness and tolerance to various types of flood are being developed by combining submergence tolerance with stagnant flooding tolerance. Accordingly, a single gene that provides resistance to submersion for up to 14 days has been found by plant breeders (International Rice Research Institute, no date).

There are numerous direct and indirect effects of rising ambient temperature on crop growth. The negative effects of higher environmental temperatures could be mitigated with the help of immediate coping mechanisms like the discovery of new crop production areas, the introduction of new crop varieties that are climate resilient, organic agriculture, cropping systems like agroforestry, rainwater harvesting systems, and micro-irrigation techniques. (Filho, 2015).

7. Conclusion

Overall, the data on observed and anticipated changes shows that Sri Lanka's climate is changing visibly, with gradual rises in temperature, altered patterns of rainfall, and a rise in the frequency and intensity of extreme weather events standing out. Sea level rise and other environmental changes are also present, and both are predicted to have a substantial impact on Sri Lanka. Paddy farming, which plays a crucial role in the agricultural sector, is one of the many aspects influenced due to climate change. Scholars have proposed several adaption strategies to counteract these negative effects which include common adaptation measures to lessen the negative effects of climate change including promoting crop insurance, growing crops that can withstand drought and floods, improving irrigation efficiency, rainwater gathering, and intercropping.

Since rice is a staple meal in Sri Lanka and is profitable economically, it will be crucial to focus on and practice the most efficient ways to deal with the difficulties posed by climate change on paddy cultivation.

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THE IMPACT OF CLIMATE CHANGE ON FOOD SECURITY: A REVIEW OF RECENT RESEARCH

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Abstract: The challenge of climate change has emerged as a paramount concern, poised to significantly impact global food security. This abstract considers recent research on the effects of climate change on food security, emphasizing its repercussions on crops, food prices, and overall food availability. The decline in output is mainly due to global warming, the unconventional nature of changes in precipitation levels, and extreme weather incidents. The unpredictability of rainfall, the status of the soil, and pests and diseases also play an important part in determining the final result. These changes are expected to cause food shortages. Due to that, developing countries such as Sri Lanka face huge problems where smallholder farmers are heavily reliant on rain-fed agriculture. Research indicates that the shifting climate is likely to result in a decline in fish stocks which could have significant consequences for the millions of individuals who depend on fish as a vital protein source. The issue is predicted to worsen in the future due to the increased population. The impact of climate change on food prices is also a concern as a secondary effect with research indicating that food prices are likely to increase due to supply shortages in the market. The anticipated outcome of this situation is poised to have a substantial impact on vulnerable communities especially those experiencing poverty as they may encounter difficulties in affording essential food items due to the low-income generation. Climate change could prompt alterations in individuals' production and consumption behaviors, potentially leading to a decrease in calorie consumption. Consequently, this may have repercussions on crop yields, food prices, and overall food accessibility. Nevertheless, farmers are embracing adaptive measures that include the utilization of hybridized and genetically modified crop varieties as well as advancements in livestock production. These strategies have the potential to contribute positively to ensuring food security.

Key words: Climate change; Food security; Global warming; Population expansion; Poverty

1. Introduction

The rise in global temperatures and environmental disruptions caused by climate change has become a significant global challenge. One of its most profound consequences is the threat it poses to food security, which is further exacerbated by factors like global warming, population growth, and persistent poverty which is rising day by day. Climate change refers to long-term changes in weather patterns and environmental conditions primarily caused by human activities, leading to detrimental effects on the planet and through that which cause unpredictable outcomes in the environment. On the other hand, food security encompasses the accessibility, availability, utilization, and stability of nutritious food for all individuals, ensuring their physical and economic well-being (El Bilali et al., 2020). Scientists widely agree with the consensus regarding the changing global climate and its expected significant impacts on food security. However, the precise nature and magnitude of these effects are still uncertain (Mekonnen et al., 2021). Meanwhile, the expansion of the population, coupled with rapid urbanization, adds additional strain to limited resources and agricultural lands, thus affecting food availability. At the same time, poverty persists as a pervasive challenge, restricting people's access to adequate food and amplifying their vulnerability to the impacts of climate change.

To determine how food production is impacted by climate change, consider its economic implications, and social aspects. Such strategies include adaptation and mitigation options. The study explores these areas that are related since the goal is to provide practical solutions towards handling concerns on climate change, and food security.

2. Methodology

This extended abstract presents a review and the summary of 15 research articles obtained from comprehensive searches on Google Scholar, Springer, Science Direct, and Scopus, focusing on the impact of climate change on food security. The objective of this review is to aim the insights into the relationship between climate change and food security by synthesizing findings from the selected articles and representing the co-relationship between the two components. The methodology employed for this review involved a systematic approach, including the formulation of inclusion and exclusion criteria, data extraction, and thematic analysis: Inclusion criteria were defined to select articles directly addressing the impact of climate change on food security and its consequences.

3. Literature Review

3.1 Food security

Food security refers to the state where individuals have reliable access to sufficient, affordable, and safe food that meets their dietary needs and preferences, enabling them to maintain a healthy and active lifestyle and further satisfy their desires. It encompasses several essential elements. Firstly, it entails ensuring a consistent, abundant, and adequate food supply for the population. Secondly, it addresses the physical accessibility of food, ensuring that people can obtain it easily and at reasonable prices because the price of food is most of the time invertedly related to the purchasing power of the consumers. Thirdly, it emphasizes the proper utilization of food, considering nutritional knowledge for optimal use and abreact the ingredients of the food in the most efficient way into human's diet. Lastly, food security encompasses the stability of food availability, access, and utilization, requiring them to be reliable and consistent over time. Despite notable progress in recent years, food insecurity continues to be a pressing issue, especially in developing countries. According to the State of Food Security and Nutrition in the World 2019 report (FAO, IFAD, UNICEF, WFP, 2019), over 820 million people suffered from hunger in 2018, with higher prevalence in regions like Africa, Latin America, and Asia. The report also estimated that over 2 billion individuals, including 8% of the population in developed nations, lacked adequate food security (Gitz et al.,2016).

3.2 Climate Change

Climate change refers to long-term changes in weather patterns and global temperatures caused by human activities, such as burning fossil fuels, land fragmentation due to growing populations, and deforestation. This results in the accumulation of greenhouse gases like carbon dioxide, in the atmosphere, trapping heat and causing environmental disruptions, finally contributing to the changes in weather patterns.

Climate change encompasses a range of effects, including rising temperatures, sea-level rise, melting ice caps and glaciers, more frequent and severe weather events (such as hurricanes, droughts, and floods), shifts in precipitation patterns, and changes in ecosystems and biodiversity. It has significant implications for various sectors, including agriculture, water resources, public health, and economies, and finally leads to the deviation of expected yield from a specific crop comparatively to its potential yield.

As agriculture depends on both macro and micro environmental changes, the variations in the precipitation hugely affect the yield difference. The consequences of climate change are far-reaching and can have both direct and indirect impacts on human societies and natural systems. These effects include disruptions to food production, water scarcity, increased frequency of extreme weather events, displacement of communities, loss of biodiversity, and negative health impacts ((Mekonnen et al., 2021).

3.3 Impact of climate change on food security

Climate change has detrimental effects on food availability, particularly in regions like Sub-Saharan Africa and South Asia. These areas heavily rely on rain-fed agriculture and are highly susceptible to climate variability and droughts. Rising temperatures, increased droughts, floods, and unpredictable weather patterns reduce crop yields, impacting staple crops like rice, wheat, and corn which are considered major energy sources for a low-income fraction of the population. Livestock productivity is also affected due to reduced forage growth and availability. And as well as animals would not be able to perform at optimum capacity and their yield can be reduced more than the breed characteristics as on the other hand, favorable environmental conditions can contribute to high yield in livestock production. The impact of climate change on fisheries, including fish populations and habitats, is still under investigation. Overall, climate change presents significant challenges to food availability, worsening food insecurity in vulnerable regions and necessitating measures to mitigate its effects.

Climate change negatively impacts food access through its effects on food prices and rural livelihoods (Hoke et al., 2019). Reduced yields and production lead to food shortages and price increases, disproportionately affecting low-income individuals, particularly in regions already facing hunger and poverty (Jenkins et al., 2016). Vulnerable populations, including urban and rural poor, struggle to afford an adequate diet, exacerbating food insecurity. Climate change also disrupts food-importing nations, restricting or prohibiting food exports and further compromising food availability and sometimes even more critical situations can lead to changes in government policies. Small island nations and landlocked countries, highly vulnerable to disruptions in food supply and trade, are particularly impacted by climate change (FAO, 2015). These impacts extend to various aspects of food systems, such as agricultural and fisheries production, food imports, distribution systems, and household food utilization (IPCC, 2014). Short-term climate variations have long-term consequences for crop yields and overall food system stability, contributing to increased price volatility (IPCC, 2014).

Climate variability resulting from climate change significantly affects food utilization and nutrition, especially among poor and vulnerable populations (Aderibigbe, 2018). Higher temperatures and water scarcity increase the risk of diseases and diminish water quality. Indigenous communities, like the Inuit in the Canadian Arctic, experience reduced access to traditional food resources, leading to decreased nutrient intake (El Bilali et al., 2020a). Climate change may reduce essential vitamins in staples and lead to poisoning. Changes in food utilization have significance for nutrition, food security as well as

NCDs related food intake. A holistic food system approach that integrates nature, governance as well as built environments should be adopted to tackle this hurdle (Aderibigbe 2018).

3.4 Global food production and challenges

Climate change is already affecting global food production, with changes in weather conditions impacting crop yields in various regions (FAO, 2015). The relationship between climate and crop yields is statistically significant in a significant portion of harvested areas worldwide, although the extent varies depending on the crop and region. Rice-harvested croplands show a higher percentage of significant relationships compared to sorghum-harvested areas globally. Yield changes range from negative values for oil palm to positive values for sugarcane, with varying percentages of change across all harvested croplands. Rice and wheat yields have declined, while corn yields have remained relatively stable among the top three global cereals. These yield changes have implications for global food calorie availability. The impact of climate change on yields varies across regions, with decreases observed in Europe, Sub-Saharan Africa, and Australia, and mixed responses in North and Central America and Asia (Ray et al., 2019).

3.5 Vulnerability of different regions and populations to climate change impacts on food security

The vulnerability of food systems to climate change is influenced by a range of factors. Socio-economic factors include access to resources, income levels, governance structures, and technological capabilities. Biophysical factors encompass soil quality, water availability, ecosystem health, and agricultural productivity. Additionally, social factors like gender dynamics, cultural practices, and institutional frameworks also play a role in shaping vulnerability. Due to this complexity, the impacts of climate change on food security are not uniformly distributed. Some regions and communities are more vulnerable and face greater challenges in adapting their food systems to the changing climate. Vulnerability can be particularly heightened in areas already grappling with poverty, limited access to resources, weak infrastructure, and political instability while other regions of the world and even other regions of the country have an abundance of food.

Addressing the vulnerability of food systems to climate change requires tailored and context-specific approaches that consider the unique challenges and opportunities in each region. It involves strengthening resilience, improving adaptive capacities, promoting sustainable practices, enhancing social safety nets, and fostering international cooperation to ensure that the most vulnerable populations are not disproportionately affected by the impacts of climate change on food security (Adu et al., 2018).

3.6 Adaptation Strategies

Small-scale farmers, who often lack the resources to effectively adapt to the impacts of climate change, have implemented various agricultural adaptation strategies. These strategies, although derived from traditional practices. They encompass the use of organic fertilizers, adjustments in planting schedules, and the cultivation of short-duration crop varieties (Ogundeji, 2022). By employing organic fertilizers, farmers can enhance soil moisture levels and provide essential nutrients to crops, resulting in increased yields. Additionally, altering planting dates and harvesting dates allows farmers to align their agricultural activities with changing rainfall patterns, optimizing growing conditions. Furthermore, the adoption of improved crop varieties, particularly those with shorter growth duration, offers increased resilience to drought conditions, leading to better harvests even during dry seasons and even to pests and diseases by introducing and modifying genes. On a global scale, the implementation of adaptation strategies such as utilizing heat-resistant and improved cultivars, adjusting cropping patterns, and expanding crop cultivation has the potential to significantly reduce the adverse impacts of climate change and mitigate the risk of hunger. Research indicates that regions experiencing mild and wet future warming may witness a substantial increase in net crop revenue, whereas hot and dry future climates could result in a significant decrease in crop revenue (Ingram et al., 2008). Notably, certain crops, such as corn, exhibit relatively low sensitivity to changing weather conditions.

Experts and farmers recommend various adaptation strategies, including crop diversification, improving neoplasm, implementing effective soil and water management practices, and as well as increasing soil fertility ensuring better access to equipment and fertilizers (Diallo et al., 2021). These measures aim to enhance the resilience of agricultural systems and contribute to mitigating the detrimental effects of climate change on global food security (Diallo et al., 2021).

3.7 Current policies and their effectiveness in addressing climate change impacts on food security

Policies aimed at reducing greenhouse gas emissions play a crucial role in addressing climate change impacts on food security. These policies often focus on transitioning to cleaner and renewable energy sources, improving energy efficiency, and promoting sustainable agricultural practices (Fujimori et al., 2018). Examples of such policies include

- Renewable Portfolio Standards (RPS) or Renewable Energy Standards (RES) that mandate a certain percentage of energy generation from renewable sources provide certification based on that.
- Carbon pricing mechanisms like carbon taxes or cap-and-trade systems, which put a price on carbon emissions to incentivize emission reductions otherwise they have to bear an extra cost as they are the people who are responsible for that.
- Agricultural policies that promote sustainable farming practices such as forestry, organic farming, and precision agriculture.

Adaptation policies are designed to help communities, farmers, and vulnerable populations adapt to the changing climate and its impacts on food security (Ingram et al., 2008). These policies focus on building resilience, improving water management, enhancing agricultural practices, and supporting rural livelihoods. Examples of adaptation policies include

- Development and implementation of climate-smart agricultural practices that are resilient to climate variability and extremes with the aid of new technology to reduce the global carbon footprint by introducing sensors instead of machine-operated implements
- Investments in irrigation infrastructure and water management systems to improve water availability for agriculture.
- Crop insurance programs to help farmers recover from climate-related losses.

(Gitz et al., 2016)

3.8 Future outlook for food security under climate change scenarios and propose recommendations to ensure food security in the long term

Under current circumstances, the prices of cereals and meats are expected to rise, reversing the long-standing trend of decreasing prices. This price increase will be driven by both factors of demand and supply, especially in the case of reducing the purchasing power due to high prices and low supply chains. The growing global population and regional economic growth will contribute to an increased demand for food. Additionally, the rising demand for meat and milk will further exert pressure on the prices of corn, coarse grains, and meats. Consequently, the world food markets will become more constrained, negatively impacting impoverished consumers. The substantial increase in food prices will lead to slower growth in calorie consumption, affecting both the food-insecure population directly through higher prices and indirectly through reduced real incomes for low-income consumers who allocate a significant portion of their earnings to food. The scarcity of resources, particularly water, is expected to increasingly limit the growth of food production as well and it becomes a fair reason for the high price tag in foods because water is considered an essential element for plant growth. This constraint is due to the competition between the demand for bio-energy and the utilization of land and water resources for food production. As the demand for bio-energy rises, the available resources for cultivating food crops face greater pressure, leading to potential conflicts in resource allocation when both of these topics come into the discussion at the same table. This situation poses challenges to sustaining and expanding food production in the face of growing resource scarcity (Rosegrant et al., 2009).

Beyond a certain threshold, the impacts of climate change on agricultural production become increasingly detrimental. While initially rising temperatures and increased carbon dioxide (CO_2) levels can benefit crops, they also accelerate evapotranspiration and necessitate sufficient water availability because when the temperature rises cellular activities of the plant cells increase, and plant water utilization increases to that plant water demand increase. This poses significant challenges for regions already constrained by water resources. Climate change exacerbates adverse effects on agriculture by diminishing water supplies, intensifying extreme events like floods and storms, causing heat stress, and promoting the spread of pests and diseases in some cases genetic pool of the natural ecosystem also can be diversified.

As global temperatures rise, especially beyond a 2-degree Celsius increase, adapting to the changing conditions becomes more difficult and costly. In areas with already high temperatures, such as the Sahel belt in Africa or South Asia, crops like wheat, which are less heat tolerant, are particularly vulnerable to immediate impacts as they are continuously subjected to the same scenario even for many years. If no effective solutions are implemented, declining crop yields, especially in regions already facing food insecurity, will further drive people into poverty. By 2030, an estimated 43 million individuals in Africa alone could fall below the poverty line due to these circumstances.

A variety of recommendations must be implemented to secure long-term food security as a country and on a global level. To begin, encouraging sustainable agriculture techniques such as organic farming and forestry can help conserve soil fertility, reduce water consumption, and protect biodiversity with minimum effects on the environment. Second, investing in agricultural research and development is critical for enhancing crop types, productivity, and resilience to climate change. It is also critical to improve rural infrastructure and market access to promote efficient transportation, storage, and connecting farmers to larger markets. Furthermore, encouraging climate change adaptation, assisting small-scale farmers, increasing international cooperation, and decreasing food waste and loss are critical tasks that can be easily achieved with the help of government policies. Finally, improving nutrition and dietary diversity through increasing access to a variety of nutritious foods is critical. We can work toward long-term food security by implementing these proposals. (Rosegrant et al., 2009)

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COASTAL ENGINEERING

ICSBE 2023-102

NUMERICAL MODELLING OF COASTAL PROCESSES FOR ENHANCED NAVIGATION THROUGH NATURALLY FORMED SUBMERGED REEFS

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Abstract: Kadamaththa, located in Dehiwala, is a fishery landing site shielded by two naturally formed coral reefs that run parallel to the beach. The existing gap between these two reefs serves as an access point for sea navigation to the fishing landing site. However, despite widening the gap in 1952, navigating through it remains challenging and hazardous, particularly during the southwest monsoon season. This is primarily due to submerged rock formations at the entrance, leading to dangerous wave-breaking actions. To address this issue, it was proposed to construct an anchorage (breakwater) on the submerged reefs, along with the removal of rocks within the approach channel area. In light of this proposal, the primary objective of this study was to evaluate the navigability and safety of the anchorage's access point, considering the proposed development on the submerged reef. Numerical simulations were conducted to analyze seasonal coastal processes, including wave disturbances, currents, and sediment transport, both in the existing conditions and with the proposed development. The conceptual layouts for the anchorage were designed based on stakeholder opinions and the assessment of existing coastal processes. To simulate hydrodynamics, sediment processes, and wave disturbances, the MIKE 21 modeling system was employed in this study. The wave disturbances were simulated under representative nearshore wave conditions using the MIKE 21 BW (Boussinesq Wave) model. The MIKE 21 HD (Hydrodynamic) model was utilized to evaluate the hydrodynamics of the anchorage entrance, basin, and surrounding areas. Further, the MIKE 21 ST (Sediment Transport) model was employed to identify sediment transport patterns and the potential for siltation within the anchorage entrance and approach channel. Based on the numerical simulation results, the suitability of the proposed anchorage layout was concluded, taking into account the navigational and safety considerations identified through the modeling process.

Keywords: Submerged reefs; Coastal process; Simulation; Navigation

1. Introduction

Kadamaththa serves as a vital fishery landing site within Sri Lanka's Colombo district, positioned near the Dehiwala railway lines (Figure 1). It has naturally evolved into a landing area and accommodates approximately 216 one-day boats. The urban fishing community, centered around this site and the adjacent coastal regions, conducts its fishing operations using the Kadamaththa landing site. Currently, the landing site is shielded by two naturally formed coral reefs that run parallel to the beach, positioned roughly 200m and 500m from the shoreline. A gap between these reefs provides a pathway for sea navigation to the fishing landing site (Figures 1 and 2). This gap was expanded in 1952. However, navigating through this gap remains challenging and unsafe during monsoon seasons due to submerged rock formations near the seaside entrance. These formations, coupled with wave-breaking actions, increase the risk of boats colliding with reefs and potentially capsizing. This perilous situation has led to loss of life and damage to fishing boats. In response, a proposal was made to construct an anchorage (breakwater) on the submerged reefs. The proposed anchorage is designed with the primary goal of enhancing navigation safety for fishery boats, particularly amid the prevailing southwest monsoon season. The necessity for this development stems from several key considerations. Firstly, it aims to ensure secure anchoring and smooth vessel operation, mitigating potential risks such as loss of life, damage to fishing crafts, and asset loss, particularly during extreme weather conditions and the monsoon period.

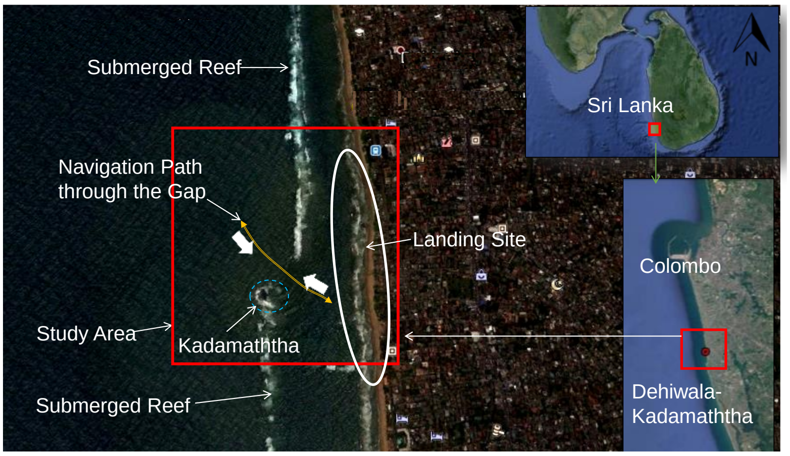

Figure 1: Study area: Existing landing site and navigation path.

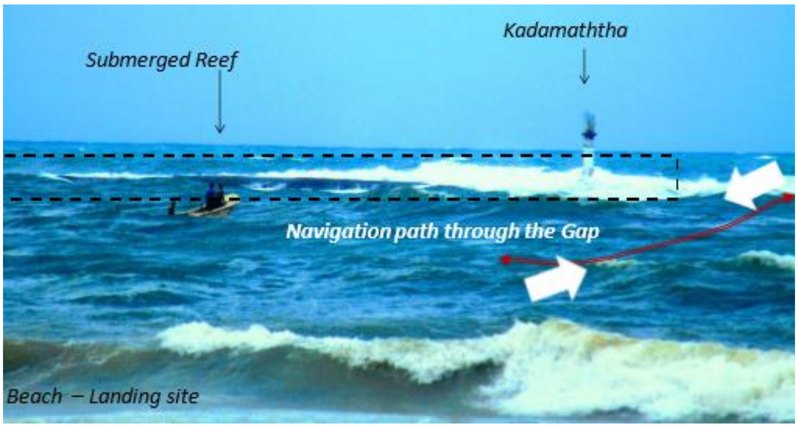

Figure 2: Navigation through the gap- View from the landing site.

Secondly, the anchorage intends to provide a protected boat landing site, enabling the local fishing fleet to sustain operations even in challenging monsoon conditions, thereby minimizing losses, damages, and operational disruptions. Thirdly, the initiative addresses economic challenges and poverty-related consequences by reducing the risks fishers currently face when operating vessels during the monsoon.

Lastly, the proposal takes into account community perceptions and experiences, acknowledging the higher fish catches reported during the monsoon compared to calmer seasons. When designing and establishing a submerged anchorage off the coastline, a comprehensive understanding of coastal processes is essential. Numerical simulation tools offer an avenue to assess coastal processes such as waves, currents, and sediment movement within the study area.

Successful outcomes from process-driven numerical modeling approaches have been demonstrated in coastal waters (Ding et al., 2006), underscoring the importance of employing advanced, process-based numerical simulation methodologies to achieve precise and effective simulations. In the context of Fishery harbors on both a global and Sri Lankan context, various coastal processes have been examined through numerical modeling (Jha et al. 2015; Laknath et al. 2017) in scientific literature. However, for all coastal processes, including wave tranquility, current, and sediment actions, at an anchorage site formed by a submerged reef, there are no specific studies in the scientific literature through numerical simulations on a global and Sri Lankan scale. Therefore, the findings from a study on these processes would be valuable for designing similar types of coastal structures with higher operational efficiency and minimal adverse coastal effects. Accordingly, the primary objective of this study was to evaluate the navigability and safety of the anchorage's access point focusing wave, current and sediment actions, using numerical simulations of coastal processes, taking into account the proposed anchorage development on the submerged reef.

2. Methodology

The suitability of the proposed anchorage layout was assessed in relation to coastal processes, including waves, currents, and sediment actions. The conceptual layouts for the anchorage were developed based on stakeholder opinions and a preliminary assessment of the existing coastal processes.

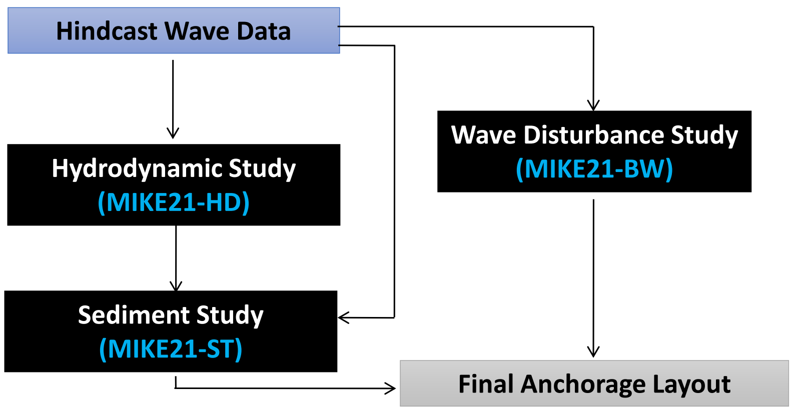

Figure 3: Numerical modeling framework.

Numerical simulations were carried out to analyze seasonal coastal phenomena, encompassing wave disturbances, currents, and sediment transport, both in the current conditions and considering the proposed development. These simulations were conducted using the DHI MIKE 21 modeling system, which enables the simulation of hydraulic and hydraulic-related phenomena in coastal waters and seas (Panigrahi et al., 2009) (Figure 3). Utilizing hindcast data for nearshore wave climate (LHI, 2018) at depths of 15m and 20m within the study area, the coastal processes were simulated to represent various wave conditions. The MIKE 21 BW model (Boussinesq Wave) was employed to examine wave behavior within the anchorage's entrance and navigational channel. This was done under different wave incidence characteristics, and the results were then compared with the guidelines recommended by the Permanent International Association of Navigation Congresses for acceptable wave conditions in medium-scale harbors (PIANC, 1995). For the analysis of current patterns, the MIKE 21 HD (Hydrodynamics) model was utilized, specifically focusing on the anchorage entrance and surrounding areas. Furthermore, the MIKE 21 ST (Sediment Transport) model was applied to identify sediment transport patterns and assess the potential for siltation within the anchorage entrance and approach channel. Based on the outcomes of these numerical simulations, the suitability of the proposed anchorage layout was assessed, taking into consideration the navigational and safety factors that were identified through the modeling process.

3. Proposed Anchorage Layout

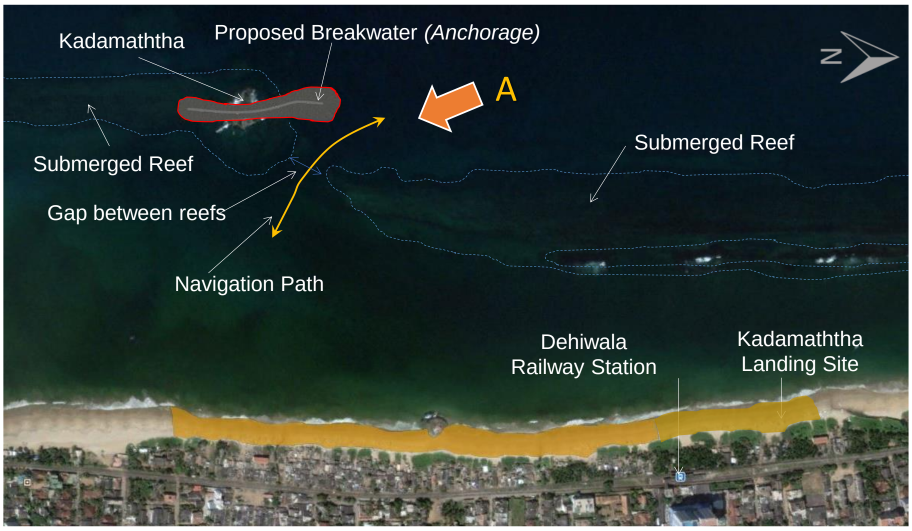

Figure 4: Proposed anchorage layout and navigation path.

Taking into consideration the stakeholders' proposals and the dominant coastal processes in the study area, the conceptually designed anchorage layout of 200m long at the Kadamaththa site is depicted in Figures 4 and 5. The existing Kadamaththa landing site is safeguarded by two coral reefs that have formed in parallel to the beach. The proposed breakwater structure has been designed to capitalize on the advantage of the submerged reef. The gap between the submerged reefs, through which navigation currently occurs, measures approximately 38m. The designed fishery anchorage is intended to serve low draft fishing boats (OFRP, NTRB, and MTRB). Therefore, the existing width of the gap is adequate for navigating from the sea area to the landing site. As shown in Figures 4 and 5, the existing navigational pathway is shielded and secured by the proposed breakwater structure during the most dominant southwest monsoon season.

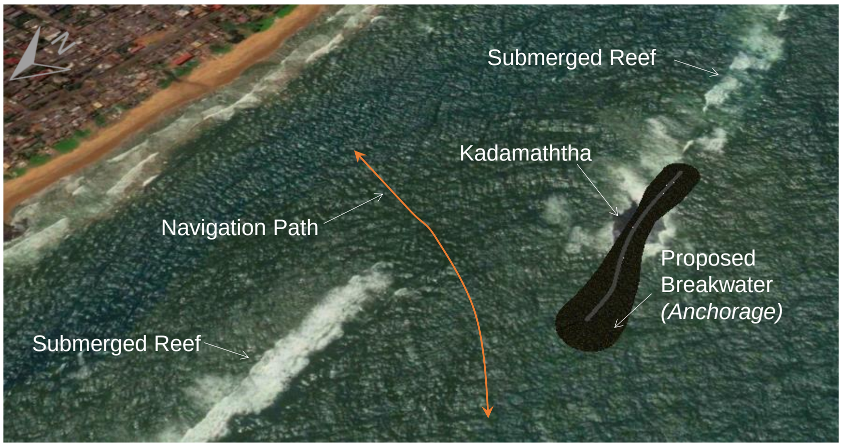

Figure 5: Proposed anchorage layout and navigation path from view A.

4. Results and Discussion

4.1. Wave Conditions in the Study Area

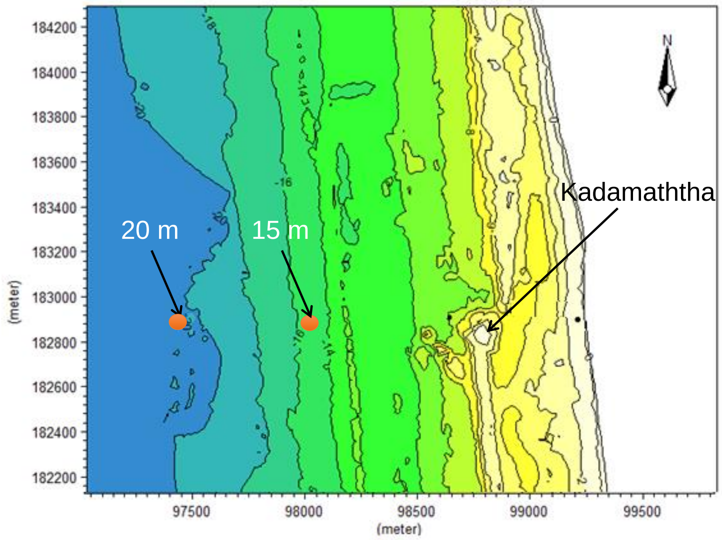

Figure 6: Wave hindcast depths (15m and 20m) in the study area.

The representative nearshore wave boundary conditions (significant wave height, peak wave period, and mean directions) for the BW, HD, and ST modules of the MIKE21 modeling system were derived from hindcast nearshore wave climate data provided by LHI (2018). This data was obtained using directional wave data originally measured at a depth of 16m in Colombo. The established wave data series at Dehiwala's nearshore, at depths of 15m and 20m, indicate that relatively high waves approach from the western direction during the southwest (SW) monsoon. In contrast, during the northeast (NE) monsoon, lower magnitude waves dominate with a narrow direction band toward the southwest. These wave conditions at depths of 15m and 20 m were utilized as the boundary conditions for the BW and HD/ST models, respectively (Figure 6). The respective wave parameters at the boundary conditions of each model will be presented in the following sections within the context of that specific model.

4.2. Wave Disturbance Study

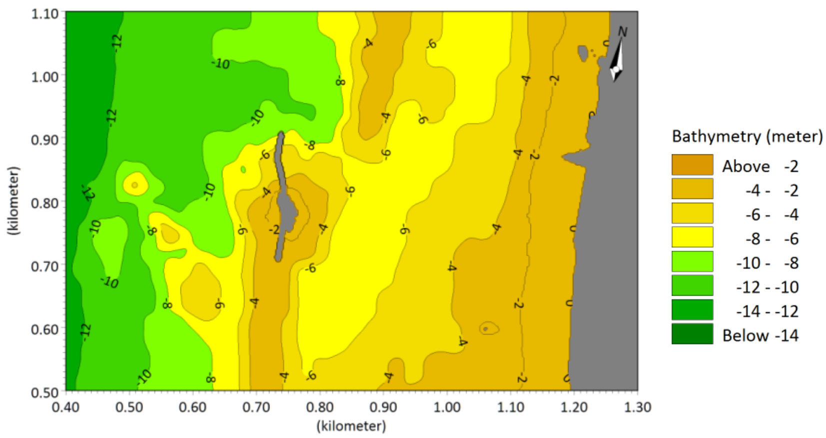

Figure 7: Proposed anchorage layout and depth variation in the study area.

The understanding of the wave disturbance at the entrance (mouth) of the anchorage, navigational channel and the sea area between the anchorage and the shoreline is one of the most important factors when engineers have to determine the optimum anchorage layout in relation to predefined criteria for acceptable wave disturbance and fishing boat movements. Specifically, understanding the wave disturbance in the sheltered area of the anchorage is important for the navigational purposes of fishing boats, as well as for mooring and handling purposes. The MIKE21 Boussinesq Wave (BW) model is a powerful tool for determining and assessing wave dynamics in ports and harbors in coastal areas. In this study, wave penetrations through the anchorage entrance and wave disturbance within the anchorage and landing site were studied using the MIKE21 BW model. These models encompass non-linearity and frequency dispersion while also demonstrating proficiency in simulating refraction, shoaling, reflection, diffraction, wave interaction, and other significant nonlinear phenomena, as highlighted by Panigrahi et al. (2015).

BW simulation requires a comprehensive set of input parameters, including bathymetry, wave boundary conditions, simulation duration, internal wave generation, eddy viscosity, bottom friction, porosity, and sponge. The primary outcomes include wave parameters (wave heights, time periods, and directions), extract at designated locations. Table 1 shows the selected wave boundary conditions for BW simulation at a depth of 15m. The "average" and "high" wave conditions were determined based on the 50% and 2% exceedance of wave parameters for the considered seasons.

The layout of the proposed anchorage with bathymetry details are shown in Figure 7. For all scenarios outlined in Table 1, the variation in wave heights within and around the proposed anchorage layout was evaluated, consequently focusing regions of wave agitation and calmness.

Table 1: Representative Wave Conditions at 15 m depth for BW model

Case No	***Season***	***Condition***	***% Exceedance***		***Wave Parameters***		
			50	**2**	**H_s(m)**	**T_p(s)**	**Dir (N^O)**
1	Southwest (SW)	Average	●		1.50	9.3	259
2	Southwest (SW)	High		●	2.30	8.8	262
3	Northeast (NE)	High		●	1.50	8.0	245
4	Inter-Monson (IM-2)	Average	●		0.50	12.5	245

Navigational hazards are correlated with the wave agitation in the sheltered area of the proposed anchorage and the area between the beach and the gap of two submerged reefs. Hence, it is essential to ensure sufficient calmness in the above area for the safe passage of fishing boats under different sea conditions. The wave tranquillity study helps to identify safe navigation in the sheltered area, through the navigational channel and the gap of the two submerged reefs, and in the area between the submerged reefs and the beach landing area for the wave conditions of the selected representative seasons.

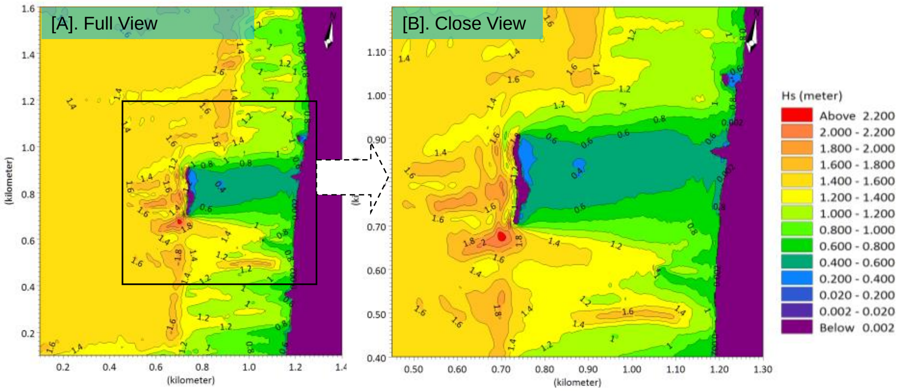

Figure 8: Significant wave heights: SW –Average wave condition (Case 1).

Comparing the durations of the prevailing seasons, the Southwest monsoon season is the longest. Additionally, the wave effect is dominant during this season, as a significant number of waves have generally high values. Therefore, when analyzing 2D plots of wave heights in the anchorage area, the outcomes of the Southwest monsoon were specially considered. In essence, for the most representative case (Case No. 1: SW – Average), the wave heights in the sheltered area (i.e., the area protected by the breakwater structure before Kadamantha Point) are around 0.4m for the proposed layout. Figure 8 illustrates the 2D plot of wave height variation in and around the proposed anchorage layouts for Case No. 1. In the SW high case (Case No. 2), wave heights in the sheltered area reach 0.8m for the proposed layouts. For the NE high case (Case No. 3), wave heights vary between 0.4m and 0.6m in the same area. In the IM – 1 average case (Case No. 4), wave heights range between 0.2m and 0.4m for the anchorage layouts, indicating a high level of calmness. There are no specific guidelines stipulated in handbooks or manuals describing the acceptable wave conditions in a fishery anchorage site of this scale. However, a comparison could be made with the guidelines recommended by the PIANC for acceptable wave conditions in medium-scale harbors (PIANC,1995), although these may not be entirely relevant for a fishery anchorage site. Given the findings of the present study, it can be considered that navigation and mooring operations are safe under these conditions, as wave heights remain within the allowable range. In general, the proposed anchorage layout with the breakwater head at a depth of 8m provides sufficient wave tranquility for anchorage operations during all seasons. Thus, the proposed layout is suitable in terms of wave tranquility.

4.3. Hydrodynamic Study

Current circulation and sedimentation are key topics that rely on a clear understanding of hydrodynamics. Therefore, a hydrodynamic study is essential to investigate the behavior of water bodies subjected to various natural forces such as waves, tides, and winds. A sound understanding of hydrodynamics in the proposed anchorage area is important because this knowledge helps determine the suitability of anchorage layout configuration, assess the possibility of safe passage for fishing boats, and comprehend sediment movement at the anchorage entrance and navigational channel.

In this study, the MIKE 21 HD (Hydrodynamic) module assesses the hydrodynamics in the proposed anchorage area. Computations were performed using a nested grid setup, starting from a larger regional model and gradually refining to smaller models as the area of interest approached. The objective of this nested approach is to utilize known tidal constituents to drive the HD model and achieve more accurate and finer grid resolutions in the area of interest. The boundary conditions for the larger "Regional Model" were based on tidal constituents from Galle and Kalpitiya. Two smaller and more refined models ("Intermediate" and "Local") were nested within this larger model. The simulations within a sub grid model are based on boundary conditions extracted from the immediately higher model. MIKE 21 HD solves the depth-averaged momentum and continuity equations to calculate the flow field. The module is forced with wind and gradients in the radiation stress field calculated by the wave module.

The outcomes include currents and mean water levels (MWL). Time series or constant surface elevations or fluxes are specified at the open boundaries. Simulations were carried out for the representative scenarios specified in Table 2. Wave effects were incorporated into the local model based on the wave conditions given in Table 2. These wave conditions are hindcast at a depth of 20m in the study area.

Table 2: Representative wave conditions at 20m depth for HD model

Case No	*Season*	*Condition*	*% Exceedance*		*Wave Parameters*		
			50	**2**	**H_s(m)**	**T_p(s)**	**Dir (N^O)**
1	Southwest (SW)	Average	●		1.50	9.4	258
2	Southwest (SW)	High		●	2.30	8.2	264
3	Northeast (NE)	High		●	1.50	8.0	242
4	Inter-Monson (IM-2)	Average	●		0.50	12.5	240

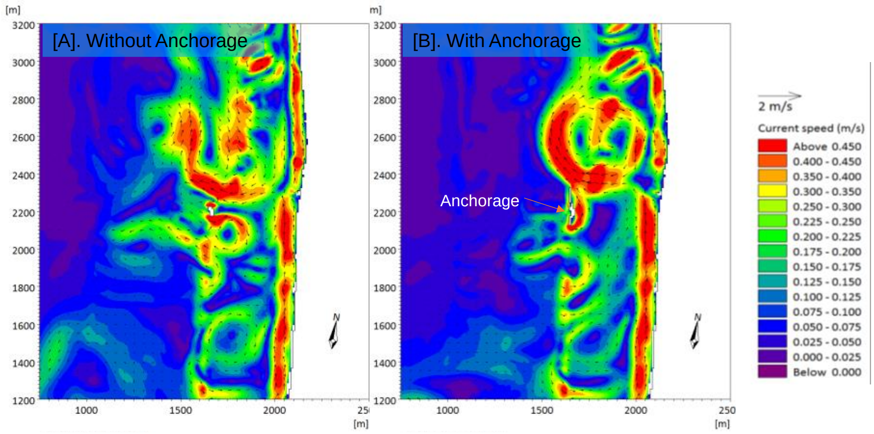

Figure 9: Two-dimensional current plots – Without (A) and with (B) for SW-Average (Case–1) for spring tide.

Simulations were conducted for scenarios defined in Table 2 to observe flow patterns and potential changes in current patterns in the study area, both for the existing conditions (without the anchorage) and with the anchorage development. The suitability of the designed anchorage layout was assessed based on identified current speed, movements and patterns in the study area. Figure 9 illustrates the 2D current plots of Case 1 (SW-Average condition) for high tide (spring) conditions, providing a general understanding of the current pattern in and around the anchorage area.

As a main observation, the anchorage location exhibits moderate current values for SW Average and SW High cases due to the presence of reefs/submerged rocks and resulting wave-induced currents. There is no significant difference in current patterns between spring and neap tide conditions, likely due to the dominance of wave-induced currents and small tidal currents resulting from a lower tidal range. For the selected representative cases, the general direction of the current movement is from south to north. Dominant current patterns are observed in two zones: near the coast and in submerged reef areas. Additionally, a current flow through the gap between Kadamantha Point and the northern edge of the submerged reef. When comparing scenarios before and after anchorage installation, there is no considerable change in current patterns along the north and south sides of the proposed anchorage location for all selected cases. Therefore, with this effect in the proposed anchorage, adverse sediment impacts (such as accretion or erosion) would likely be minimal for the beach area near the anchorage. Overall, considering the possibility of current speed occurrence, current patterns and magnitude (approximately average of 0.5 m/s), the simulated current values could be considered acceptable for navigation. Thus, the proposed anchorage configuration is favorable for hydrodynamic performance.

4.4. Sediment Transport Study

Sediment is transported due to nearshore hydrodynamics along the shore (littoral drift) and cross-shore. Assessing sediment movement in the proposed anchorage location helps determine the possibility of sediment transport, accumulation, and erosion. Waves, wave-induced currents, and other sea currents (such as tidal currents) are the dominant forces causing this transport. In this study, we used the MIKE 21 ST model for sediment analysis. MIKE 21 ST is the sediment transport module of the MIKE 21 modeling system used to assess the transport rates of non-cohesive sediment (sand) resulting from the current or combined wave-current flow. It calculates sediment transport rates on a rectangular grid covering the area of interest, based on hydrodynamic data from a MIKE 21 HD simulation and wave parameters computed by MIKE 21 SW. This calculation employs wave and current theories, utilizing Bijker's method (Bijker, 1971). Table 3 provides the selected wave conditions at a depth of 20 m for sediment transport modeling. Representative "average" wave conditions for each monsoon and related hydrodynamic conditions were used for simulations and subsequent sediment transport pattern assessment.

Table 3: Representative wave conditions at 20m depth for ST model

Case No	*Season*	***Wave Parameters***		
		H_s(m)	**T_p (s)**	**Dir (N^O)**
ST1	SW - Average	1.50	9.4	258
ST2	IM-1- Average	1.50	9.4	258
ST3	NE- Average	0.50	12.5	240
ST4	IM-2- Average	0.50	12.5	240

To identify potential sediment transport patterns around the anchorage, model outputs are presented in 2D sediment transport rate plots. Thus, the sediment capacity entering through the anchorage entrance for each season is compared with the transport rate.

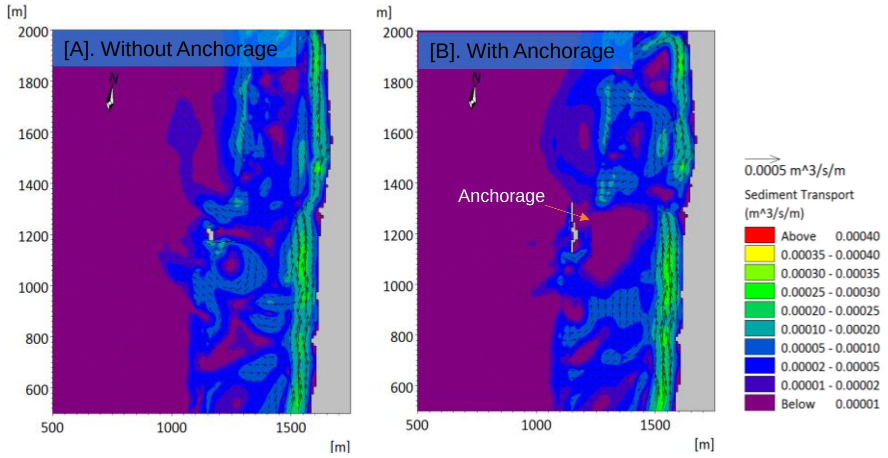

Figure 10: Two-dimensional Sediment transport rate plots – Without (A) and with (B) for SW-Average (Case–ST1).

Sediment transport patterns were compared between scenarios "without" and "with" the anchorage. As an example, the 2D sediment transport rate for the SW-Average case (ST1 in Table 3) under both "with" and "without" anchorage conditions is shown in Figure 10.

As a primary observation, two types of sediment transport patterns are identified. Longshore sediment transport (LST) is visible in the surf zone, as expected. Additionally, due to wave-induced currents in the submerged reef area, sediment transport patterns are observed on both sides of the submerged reefs. However, sediment transport rates in the reef area are lower compared to LST rates. It is noted that sediment transport during the SW monsoon is more significant than in other seasons. Relative to other seasons, sediment transport rates are lower in NE-Average and IM-2 Average seasons. With the proposed anchorage layout, sediment transport patterns have changed in the sheltered area and the gap, indicating a reduced likelihood of sediment accumulation. In the navigation area (sheltered area and the gap), sediment transport patterns have been directed to both in and out directions for both "without" and "with" anchorage conditions. With the anchorage layout, sediment inflow has decreased during significant seasons (SW-Average, SW-High, and IM-1). Comparing "without" and "with" anchorage conditions for all seasons, it is evident that the proposed anchorage configuration has not led to an increase in the net sediment transport rate towards the anchorage through the entrance, indicating less potential for siltation in the navigational channel and the anchorage entrance area.

4.5. Applicability of Research Outcome

Different modules of the MIKE21 modeling system were used in this study to identify coastal processes such as wave tranquility, wave and tide-induced currents, and sediment actions. Generally, the MIKE21 modeling system has been identified as a reliable model for simulating coastal processes. Numerical simulation work for the development of Colombo Port (Gunawardena and Ligteringen, 2003) and Wennappuwa Fishery Harbor (Laknath et al. 2017) can be given as similar and successful applications of the MIKE21 modeling system in the Sri Lankan context, demonstrating its robustness and accuracy for different layout configurations. However, since the spectral model (SW) of MIKE21, has limitations in accurately simulating wave phenomena like reflection and diffraction (Oh, 2009), the MIKE21 BW model was used in this study. Specifically, the BW module of MIKE21 is considered an accurate phase-resolving numerical model as it can simultaneously simulate diffraction and reflection, as opposed to a phase-averaged wave model. MIKE21 HD and ST models are depth-averaged models that average the flow properties over the vertical depth of the water column. Generally, coastal areas with complex coastal processes, strong tidal currents, and other intricate features may require more sophisticated three-dimensional models for accurate representation of flow dynamics. However, as such complexity is not present in our study area, we relied on the depth average results of the HD and ST models.

As the outcome of this study, we developed a numerical modeling methodology to identify existing coastal processes for easy and safe navigation through naturally formed coral reefs. This could be applicable for similar cases in local and global contexts. Furthermore, the research outcome was useful for the optimization of the proposed coastal structure in terms of minimizing adverse coastal issues such as wave agitation and high current actions at the navigation channel, as well as sediment accumulation. Additionally, with the optimized design, it will be helpful to construct the designed structure with the minimum cost.

5. Conclusions

The present study was conducted to investigate the suitability of the proposed fishery anchorage at Kadamaththa in Dehiwala, which is shielded by two naturally formed coral reefs that run parallel to the beach. The existing gap between these two reefs serves as an access point for sea navigation to the fishing landing site, and navigating through it remains challenging and hazardous, particularly during the southwest monsoon season. Considering the unsafe navigation through the entrance and the requirements of the stakeholders, an anchorage (breakwater) layout was proposed by taking advantage of the submerged reefs at Kadamaththa Point. Accordingly, the primary objective of this study was to evaluate the navigability and safety of the anchorage that will be developed on the submerged reef.

From the wave disturbance study, it was identified that navigation and mooring operations in the sheltered area, the navigational channel, and through the gap of the two submerged reefs, as well as in the area between the submerged reefs and the beach landing area, are safe as wave heights remain within the allowable range recommended by PIANC. Thus, the proposed anchorage layout provides sufficient wave tranquility for anchorage operations during all seasons. From the hydrodynamic study, it was identified that the anchorage location exhibits moderate current values for the dominant southwest monsoon due to the presence of reefs/submerged rocks and resulting wave-induced currents. Further, the general direction of the current as well as sediment movement is from south to north and dominant during the southwest monsoon season. Dominant current patterns are observed in two zones: near the coast and in submerged reef areas. Additionally, it was identified that a current flow takes place through the gap between Kadamaththa Point and the northern edge of the submerged reef. Considering the possibility of current speed, patterns, and directions, the simulated current values could be considered acceptable for navigation. Thus, the proposed anchorage configuration is favorable for hydrodynamic performance. From the sediment transport study, in addition to longshore sediment transport (LST) being visible in the surf zone, sediment transport patterns were observed on the seaward sides of the submerged reefs due to wave-induced currents in the submerged reef area. However, sediment transport rates in the reef area are lower compared to LST rates. With the proposed anchorage layout, sediment transport patterns have changed in the sheltered area and the gap, indicating a reduced likelihood of sediment accumulation. Comparing "without" and "with" anchorage conditions for all seasons, it is evident that the proposed anchorage configuration has not led to an increase in the net sediment transport rate towards the anchorage through the entrance, indicating less potential for siltation in the navigational channel and the anchorage entrance area. Based on the numerical simulation results, the suitability of the proposed anchorage layout was concluded, taking into account the navigational and safety considerations identified through the modeling process.

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HARBOUR DEVELOPMENT IN BALAPITIYA: INSIGHTS FROM NUMERICAL MODELING OF COASTAL PROCESSES

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Abstract: The study focuses on the proposed harbor development in Haraspola Bay, Balapitiya, which benefits from the natural protection of the existing rocky headland on its southern side. Inadequate berthing facilities and unsafe navigational conditions currently hinder efficient fishing activities in the fishing landing site. The conceptual harbor layout considered stakeholder requirements and existing coastal processes to enhance operational efficiency. An accurate assessment of coastal processes is essential to understand their behavior and design harbor layouts with minimal adverse effects from coastal processes. Therefore, this study aims to simulate wave, current, and sediment actions for the proposed harbor, ensuring safe navigation and minimizing adverse effects from coastal processes. The MIKE 21 modeling system was employed for this purpose. Using hindcast nearshore wave climate data, coastal processes were simulated for representative wave conditions. The MIKE 21 BW (Boussinesq Wave) model was utilized to study wave disturbance and ensure that simulated wave heights fall within acceptable limits for safe navigation and mooring operations. The MIKE 21 HD (Hydrodynamics) model results confirmed the favorable hydrodynamic performance of the proposed harbor configuration. To investigate potential siltation issues, the MIKE 21 ST (Sediment Transport) model was used to analyze sediment transport patterns, particularly at the harbor entrance and approach channel. While sediment transport rates were more significant during the southwest monsoon, the movement of sediment into the harbor through its entrance is limited. Therefore, the proposed harbor layout is expected to facilitate sediment bypass. In conclusion, the numerically simulated results justify the suitability of the chosen harbor location and layout. By considering stakeholder requirements and understanding coastal processes, the harbor design ensures safe navigation, optimizes hydrodynamic performance and minimizes potential siltation problems. This study highlights the importance of accurately assessing coastal processes in developing a harbor that promotes efficient fishing activities while mitigating adverse effects from waves, currents, and sediments.

Keywords: Harbour development; Coastal processes; MIKE 21; Numerical modelling

1. Introduction

Haraspola is a fishery landing site located approximately 6 km north of Balapitiya in the Galle district, within the Southern province of Sri Lanka. Fishermen have utilized this location for an extensive period due to its superior boat sheltering capabilities. The primary focus of this study is the envisioned development of a harbor within Haraspola Bay, which capitalizes on the natural protection afforded by the existing rocky headland to its southern side. The current deficiency in berthing facilities and precarious navigational conditions presently impede efficient fishing operations at this landing site. The proposed harbor layout has been formulated based on stakeholder requirements and established coastal processes, while also considering the impact of monsoonal waves and potential littoral drift direction. Nonetheless, a precise evaluation of coastal processes is imperative to comprehend their dynamics and enhance harbor layouts while minimizing adverse coastal effects. The assessment of coastal processes can be facilitated through the utilization of numerical simulation tools and techniques aimed at simulating these processes within the study area. In coastal waters, process-driven numerical modeling approaches have showcased successful outcomes (Ding et al., 2006), emphasizing the significance of employing cutting-edge process-based numerical simulation methodologies to achieve accurate and effective simulations. Consequently, the primary objective of this study is to simulate wave, current, and sediment actions within the proposed harbor, thereby ensuring secure navigation and mitigating detrimental effects arising from coastal processes. This endeavor will employ state-of-the-art numerical modeling techniques and methodologies.

2. Study Area

The proposed fishery harbor site is situated approximately 1.2 km north of the Maadu River mouth and within 700 m of the Colombo-Galle main road. The closest harbors to the intended landing site are Ambalangoda and Beruwala. Traditionally, the coastal stretch of the proposed area has been utilized by villagers for fishing activities. The northern part of the existing landing site serves beaching operations, while a small bay area, featuring a headland, is used for landing small fishing vessels, including Outboard Engine Fiberglass Reinforced Plastic Boats (OFRP) and Non-motorized Traditional Boats (NTRB). The proposed site shares a boundary with a sizable rock formation, Haraspola, which demarcates the site's southern limit. Presently, a significant concentration of smaller-scale mechanized and non-mechanized vessels cluster in Haraspola, leaving them susceptible to adverse weather conditions without secure anchoring provisions.

Figure 1: Study area: Proposed harbor site and existing landing site.

In contrast, within the Balapitiya Fishery Inspection (FI) division, there are no anchoring facilities accessible for Inboard Multi-day Boats (IMUL). It has been noted that efficient fishing operations are hindered at the Haraspola landing site due to insufficient and unsafe berthing facilities. The proposed Haraspola site is a bay encircled by rocks on its southern edge, featuring a broad beach suitable for landing activities. The presence of an existing rocky headland on the southern side provides a natural degree of shelter, helping to mitigate wave impact during the southwest monsoon period. Additionally, the ample natural depths of around 5 m at the proposed anchorage mouth provide favorable coastal attributes for the harbor development at the Haraspola landing site. The wave climate is primarily composed of long swell waves, mainly originating from the southern direction, and larger yet shorter wind-generated waves from the southwest during the southwest monsoon period, which spans from May through September. Throughout the northeast monsoon season, which occurs from December to February, wind waves typically approach from a more northern direction and are limited in size. Sediment transport direction varies by the wave direction. Generally, sediment transportation occurs northward, with a smaller component moving in the southern direction. Consequently, the beach on the southern side of the headland appears considerably wider than that on the northern side. The seafloor of the nearshore coastal area, adjacent to the beach, consists of a clear sandy expanse, lacking significant floral diversity.

3. Methodology

In line with the objective of the present study, field observations were conducted along the potential harbor site to assess the current situation, suitability for the development of a harbor, current coastal processes, and their impact on the coastline. Furthermore, stakeholder meetings were held to understand the requirements, interests, concerns, and proposals of key stakeholders, including the local community, government organizations, fishermen, and individuals involved in tourism in the area. Additionally, key informant surveys were used to gather in-depth information and suggestions for the proposed development. Based on the outcomes of field observations, which included seasonal coastal processes in the area, and stakeholder requirements, a conceptual layout was developed for the proposed harbor. The developed conceptual layout was further refined into a harbor master plan using the outcomes of numerical model results. Numerical simulations were conducted using the DHI MIKE 21 modeling system to analyze coastal processes for both existing conditions and the proposed master plan of the harbor configuration. The MIKE 21 modeling system enables the simulation of hydraulics and hydraulic-related phenomena in coastal waters and seas (Warren et al., 1992). Using hindcast nearshore wave climate data (LHI, 2018), coastal processes were simulated for representative wave conditions. Wave disturbance within the fishery harbor entrance and basin was studied using the MIKE 21 BW model (Boussinesq Wave) under various wave incidence characteristics, and the outcomes were compared with the guidelines recommended by the Permanent International Association of Navigation Congresses (PIANC) for acceptable wave conditions in medium-scale harbors. For the analysis of current patterns and assessment of sediment transport, the MIKE 21 HD (Hydrodynamics) and ST (Sediment Transport) models were employed, particularly at the fishery harbor mouth and basin. Based on the results, layout modifications, and optimizations were implemented to ensure basin tranquillity and minimize adverse hydrodynamic and sediment effects. Finally, the engineering feasibility of the proposed harbor was evaluated, considering factors such as changes in erosion and accretion patterns near the harbor, wave tranquillity in the harbor mouth and basin, and the sustainability of the navigational channel concerning siltation and potential dredging operations.

4. Results and Discussion

4.1 Stakeholder's Needs

There are four primary fisheries harbors (Galle, Dodanduwa, Hikkaduwa, and Ambalangoda) situated in the Galle District that mainly accommodate multi-day boats (IMUL). According to the design specifications of these four harbors, the available berthing capacity for a total of 700 IMUL vessels (ranging from 3.5 to 5 tons) falls short of the current IMUL fleet operating in the Galle district, which is estimated to be 751 at present. Based on the current information (MFARD, 2017), there are a total of 665 active fishermen engaged in fishing within the Balapitiya FI Division in the Galle district. They produced 885,470 kg of catch using 137 fishing crafts, including 100 OFRP, 15 NTRB, and 22 beach scenes (Madel). Despite the presence of four fisheries harbors functioning in the district to accommodate multi-day boats, substantial congestion and limitations persist. Stakeholder consultations have revealed that IMUL boats encounter navigational and landing difficulties due to factors such as sand accumulation at the harbor mouth during certain times of the year (Hikkaduwa), design failures (Dodanduwa), susceptibility to accidents during monsoons (Ambalangoda, Dodanduwa), and berthing congestion (Galle). In addition to technical constraints, operators/owners of multi-day boats who are not from the harbor's specific area face several other difficulties, including lower priority for unloading/loading and extra costs for transporting crewmembers and providing security after berthing. Smaller fishing vessels, particularly OFRP, mechanized, and non-mechanized traditional crafts, operate in the district and are anchored or beached at natural sheltered landing sites, primarily located in bays and adjacent to headlands. Alongside naturally sheltered bays, a few locations at river mouths and lagoons offer landing sites for smaller fishing vessels in the Galle fisheries district. The Balapitiya fish-landing site situated in the Madu River Estuary is considered a potential harbor site. However, keeping this entrance open throughout the year proves challenging due to substantial siltation, making navigation unsafe for fishing vessels. Previous attempts by the Ministry of Fisheries and Aquatic Resources Development (MFARD) to construct an anchorage and provide berthing facilities for multi-day boats in the Maduganga outlet were unsuccessful due to regular sand bar formation. With the absence of a suitable harbor facility for multi-day boats in the region, boat owners have had to operate primarily from Beruwala and Galle, both approximately 20 km away from Balapitiya. Consequently, the expectations of both multi-day boat operators and other fishers (OFRP, NTRB, MTRB) in the area are quite high.

In this context, the proposed site at Haraspola is a bay bordered by rocks on its southern side and features a spacious beach suitable for landing purposes. Additionally, natural depths of up to 5 meters at the proposed harbor entrance were identified as advantageous coastal features for the development of a fishery harbor at the Haraspola landing site. The foremost need of fishermen is protection from southwest monsoon waves during navigation to the landing site, ensuring safe navigation. Accordingly, they suggest constructing a harbor by connecting the available rocks (both exposed and submerged) on the southern side of the bay, leveraging the existing natural shelter provided by the rock headland. The proposed harbor at Haraspola is expected to address the long-standing infrastructure requirement of the marine fisheries sector (IMUL, OFRP, NTRB, MTRB fishing boats) in the division. Therefore, the necessity for a harbor at Haraspola must be examined and explored considering the engineering, social, and economic requirements of the marine fisheries sector in the district, as well as the prevailing environmental conditions. This study specifically focuses on the engineering perspective.

4.2 Proposed Harbour Layout

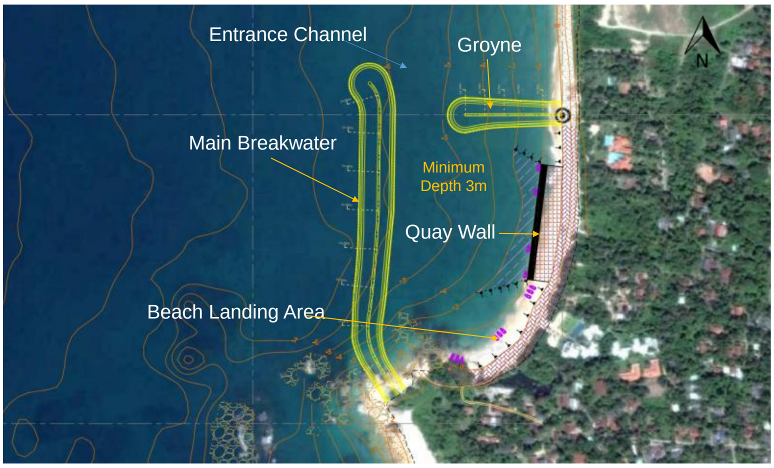

Figure 2: Proposed harbor layout.

According to the identified stakeholder requirements and perceived coastal processes in the area, the proposed harbor layout is depicted in Figure 2. Within this layout, the Main Breakwater and the Groyne structures have a combined total length of 543 m. The designated harbor basin spans an area of 5.00 hectares, featuring a dredging depth of 3 meters. The provided entrance channel, boasting a width of 78 m, adequately accommodates two-way navigational routes through the harbor entrance. The depth at the harbor mouth ranges from -5.0 meters to -6.0 meters MSL (Mean Sea Level). The design of the fishery harbor aims to cater to IMUL, OFRP, NTRB, and MTRB fishing boats. The suitability of this layout from the coastal engineering point of view will be further studied with the outcome of the numerical model results.

4.3 Numerically Simulated Coastal Processes

4.3.1. Wave Conditions

The representative nearshore wave boundary conditions (significant wave height, peak wave period, and mean directions) for the BW, HD, and ST modules of the MIKE21 modeling system were derived from hindcast nearshore wave climate data provided by LHI (2018), which was based on wave measurements in Galle at a depth of 70 meters.

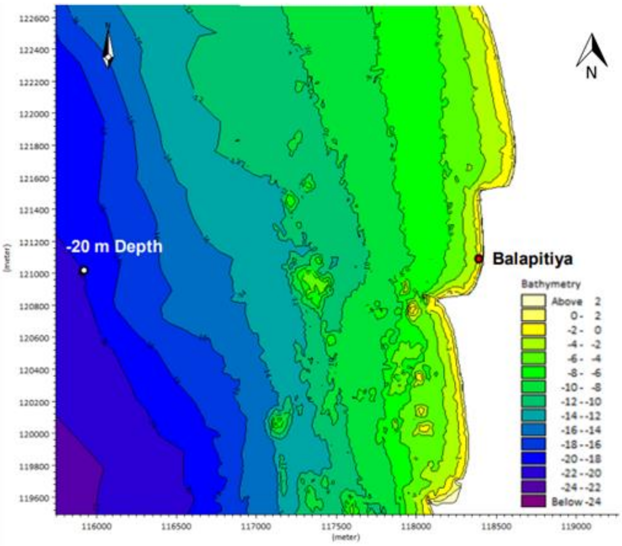

Figure 3: Depth variation in the study area and 20 m depth.

These wave conditions, originally measured at a depth of 70 meters, were employed as the boundary conditions for both the BW and HD/ST models (refer to Figure 3). The respective wave parameters at the boundary conditions of each model will be presented within the context of that specific model.

4.3.2. Wave Tranquility Study

Understanding wave disturbances at the harbor entrance (mouth) and inside the basin is a pivotal consideration for engineers when determining the optimal harbor layout by predefined criteria governing acceptable wave disturbances, fishing boat movements, and mooring arrangements. Precisely, comprehending wave disturbances within the harbor basin holds significance for both the navigational aspects of fishing boats and the practicalities of mooring and handling. The MIKE21 Boussinesq Wave (BW) model stands as a robust tool for the assessment and determination of wave dynamics in coastal ports and harbors. Boussinesq Wave Models possess the capability to represent all primary physical phenomena of water waves in shallow seas and harbors, as affirmed by Barve et al. (2015). These models encompass non-linearity and frequency dispersion, while also demonstrating proficiency in simulating refraction, shoaling, reflection, diffraction, wave interaction, and other significant nonlinear phenomena, as highlighted by Panigrahi et al. (2015).

Table 1: Representative Wave Conditions at 20 m depth for BW model

Case No	*Season*	*Condition*	*% Exceedance*		*Wave Parameters*		
			50	**2**	**H_s(m)**	**T_p(s)**	**Dir (N^O)**
1	Southwest (SW)	Average	●		1.90	6.6	223
2	Southwest (SW)	High		●	2.90	6.6	240
3	Inter-Monson (IM-1)	Average	●		1.50	6.2	217
4	Northeast (NE)	High		●	1.10	5.7	192

This study specifically investigates the penetration of waves through the harbor entrance and the wave disturbance (agitation) inside the harbor basin through the utilization of the MIKE21 BW model. BW simulation necessitates a comprehensive set of input parameters, including bathymetry, wave boundary conditions, simulation duration, internal wave generation, eddy viscosity, bottom friction, porosity, and sponge. The primary outcomes encompass wave parameters (wave heights, periods, and directions), retrievable at designated locations. Refer to Table 1 for the selected wave boundary conditions for BW simulation at a depth of 20 meters. The "average" and "high" wave conditions were determined based on the 50% and 2% exceedance of wave parameters for the considered seasons. For all scenarios outlined in Table 1, the variation in wave heights within and around the proposed harbor layout was evaluated, consequently pinpointing regions of wave agitation and calmness. An illustration depicting the significant wave heights for the Southwest (SW) - High wave condition (Case 2) can be found in Figure 4.

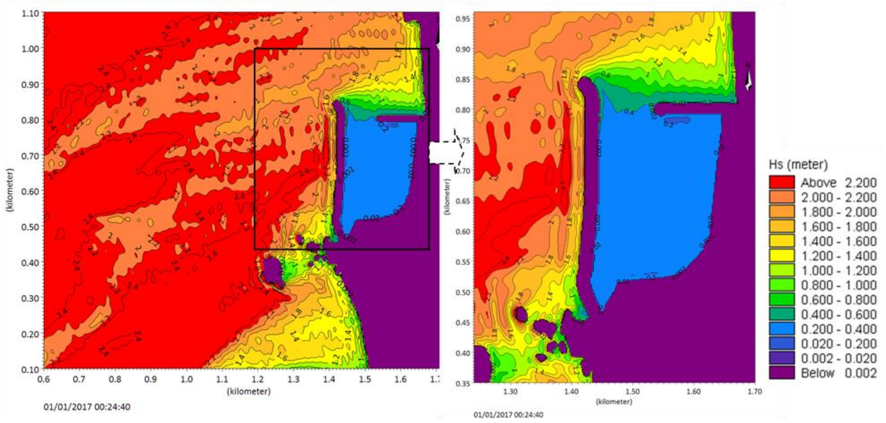

Figure 4: Significant wave heights: SW –High wave condition (Case 2).

Navigational hazards are correlated with wave disturbances at the harbor entrance. Thus, ensuring sufficient calmness at the harbor mouth for the safe passage of fishing boats under varying sea conditions is essential. The reduced depth at the entrance (harbor mouth) could lead to depth-induced wave breaking, resulting in hazardous conditions for fishing boats navigating across the harbor entrance.

When comparing the durations of different seasons, the SW monsoon season emerges as the lengthiest. Moreover, wave effects dominate during this season due to the prevalence of generally high wave values. Therefore, while analyzing 2D plots of wave heights in the harbor area, the impact of the SW monsoon was specifically considered. In the case of the most representative scenario (Case 1 – SW – average), wave heights in the basin area are observed around 0.2 meters within the harbor. At the harbor entrance, wave heights vary between 0.2 meters and 0.6 meters, indicating greater calmness. In the SW -High case (Case 2), wave heights in the basin area reach around 0.4 meters, while at the entrance area, they fluctuate between 0.4 meters and 0.8 meters. Similar patterns of lower wave heights at both the entrance and basin compared to Case 1 were observed for the other scenarios (Cases 3 and 4). The simulation outcomes were compared with the guidelines recommended by the Permanent International Association of Navigation Congresses (PIANC) for acceptable wave conditions in medium-scale harbors. Based on the assessment results, safe navigation through the harbor entrance was assured for all seasons. Consequently, considering the findings of this study, navigation and mooring operations can be deemed safe under these conditions, as wave heights remain within the permissible range.

4.3.3. Hydrodynamic Study

Current circulation and sedimentation are some of the key topics relying on a clear understanding of hydrodynamics. Thus, hydrodynamic study is essential to investigate the behavior of water bodies subjected to a variety of natural forces such as waves, tide, and wind. Sound understanding of the hydrodynamics in the proposed harbor area is important as that knowledge helps to decide the configuration of the harbor layout, the possibility of safe passage for fishing boats, and understanding the sediment movement inside and in the vicinity of the harbor. In this study, the DHI MIKE 21 HD (hydrodynamic) module assesses the hydrodynamic of the basin and the neighborhood of the proposed harbor area. Computations were performed on a nested grid set-up starting from a larger regional model and gradually reducing to smaller models while moving toward the area of interest. The objective of this nested approach is to use known tidal constituents to drive the HD model and to arrive at more accurate and finer grid resolutions towards the area of interest. The boundary conditions for the larger "Regional Model" were based on the tidal constituents from Galle and Kalpitiya. Two small and more refined models ("Intermediate" and "Local") were nested within this larger model. The simulations within a sub-grid model are based on boundary conditions extracted from the immediately higher model. MIKE 21 HD solves the depth-averaged momentum and continuity equations to calculate the flow field. The module is forced with wind, and gradients in the radiation stress field are calculated by the wave module. The currents and the mean water level (MWL) are calculated as the outcome. Time series or constant surface elevations or fluxes are specified at the open boundaries. Simulations were carried out for the representative scenarios specified in Table 1. The wave effect was incorporated into the local model respective to the wave conditions given in Table 1.

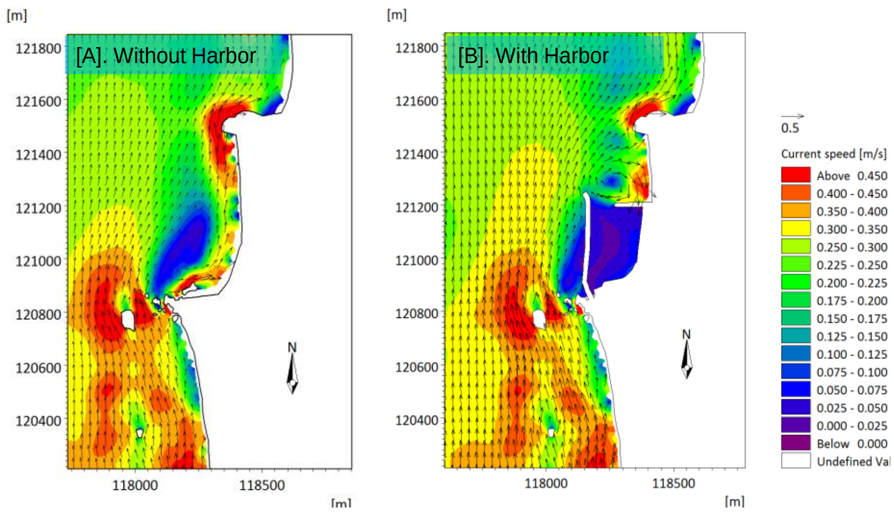

Figure 5: Two-dimensional current plots – Without (A) and with (B) for SW-High (Case–2) for spring tide.

Simulations were carried out for scenarios defined in Table 1 to observe the flow patterns and potential changes of current patterns in the study area, both for the existing condition (without a harbor) and with the harbor development. The suitability of the designed harbor layout was assessed based on identified current movements and patterns in the study area. Figure 5 illustrates the 2D current plots of Case 2 (SW-High condition) for high tide (spring) conditions, providing a general understanding of the current pattern in and around the harbor. Notably, the harbor location exhibits low current values for all scenarios due to the shelter provided by the rocks on the southern side. In the selected representative cases, the prevailing current direction generally moves from south to north. There's no significant difference in current patterns between spring and neap tide conditions, likely due to the dominance of wave-induced currents and the relatively small tidal currents resulting from a lower tidal range. Under SW monsoon average and high wave conditions, heightened current activity is observed north of the proposed harbor. Nevertheless, based on site observations and fishery community experience, no visible sand accretion/erosion resulting from this effect has been noted in the proposed harbor location. The layout of the proposed harbor effectively minimizes this effect. During northeast high seasons, current effects are not particularly strong at the harbor mouth or in its vicinity, indicating that the proposed harbor would not contribute to adverse sediment actions. It's worth noting that most of the current velocities generated by waves and tides remain below 0.14 m/s in the selected location with the proposed harbor.

4.3.4. Sediment Transport Study

Sediment is transported due to nearshore hydrodynamics along the shore (i.e. littoral drift) and cross-shore processes. Assessing sediment movement in the proposed harbor location enables us to determine the extent of sediment transport, accumulation, and erosion possibilities. Waves, wave-induced currents, and other sea currents (e.g. tidal currents) are the dominant forces causing this transport. In this study, we employed the MIKE 21 ST model for sediment analysis. MIKE 21 ST is the sediment transport module of the DHI MIKE 21 modeling system used to assess sediment transport rates of non-cohesive sediment (sand) resulting from current or combined wave-current flows. It calculates sediment transport rates on a rectangular grid covering the area of interest, based on hydrodynamic data obtained from a MIKE 21 HD simulation and wave parameters computed by MIKE 21 SW. This calculation is performed using wave and current theories, applying Bijker's method (Bijker, 1971). To calibrate the ST model, sediment properties, bed roughness values (M), and bed load transport coefficient (B) were utilized. Table 2 presents the selected wave conditions for sediment transport modeling. Accordingly, representative "average" wave conditions for each monsoon and related hydrodynamic conditions were employed for simulations and subsequent assessment of sediment transport patterns.

Table 2: Wave Conditions for ST Model Simulations

Case No	*Season*	*Wave Parameters*		
		H_s(m)	**T_p(s)**	**Dir (N^O)**
ST1	SW - Average	1.90	6.6	223
ST2	IM-1- Average	1.90	6.6	223
ST3	NE- Average	1.10	5.7	192
ST4	IM-2- Average	1.90	6.6	223

To identify possible sediment transport patterns in the vicinity of the harbor, model outputs are presented in two-dimensional sediment transport rate plots. Thus, the amount of sediment capacity entering through the harbor entrance for each season is compared with the transport rate. Sediment transport patterns were compared between "without" and "with" harbor conditions. As an example, the 2D sediment transport rate for the SW-Average case (ST1 in Table 2) under both with and without harbor conditions is provided in Figure 6.

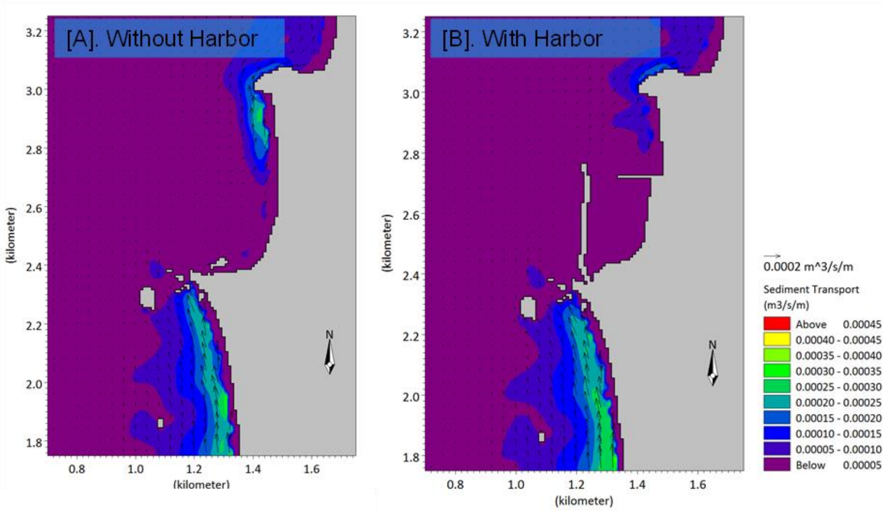

Figure 6: Two-dimensional Sediment transport rate plots – Without (A) and with (B) for SW-Average (Case–ST1).

As a primary observation from the comparison of sediment transport plots, low sediment transport rates were noted in the entrance area of the proposed harbor. After contrasting the 'without' and 'with' harbor conditions across all seasons, it becomes evident that the proposed harbor configuration has not led to an increase in sediment transport rates toward the harbor through its entrance. Furthermore, it has been determined that the sediment transport rate is particularly significant during the SW monsoon compared to other seasons. The predominant direction of sediment transport during the SW monsoon is from south to north. However, this sediment transport movement has not significantly contributed to sediment accumulation within the harbor basin through its entrance. Consequently, the configuration with the outer bend breakwater design at the harbor mouth is likely causing sediment diversion toward the offshore side and potential sediment bypass through the harbor mouth with the proposed layout.

To gain a comprehensive understanding of seasonal and long-term sediment transport patterns as well as shoreline evolution on the north and south sides of the proposed harbor location, an extensive field survey was conducted from October 23 to October 29, 2018. Several processes were identified, including (1) local and seasonal sediment transport processes within the bay area on the north and south sides of the harbor (2). due to its location in a sheltered bay area, the proposed harbor is minimally impacted by adverse sediment processes. These observations further support the confirmation of the lack of adverse impacts from sediment-related actions on the designated area with the development of the proposed harbor.

5. Conclusions

The present study was conducted to investigate the suitability of a fishery harbor at Haraspola Bay in Balapitiya, which benefits from the natural protection of the existing rocky headland on its southern side. Before conducting the numerical model study, stakeholder needs for the harbor and the suitability of the proposed site were assessed through field observations and a preliminary understanding of coastal processes in the study area. While developing the conceptual layout and master plan of the harbor, stakeholder proposals were taken into consideration, and relevant requested features were integrated into the design.

To comprehend coastal processes, such as waves, currents, and sediment movements, the MIKE 21 modeling system was employed in this study. Specifically, the MIKE 21 BW (Boussinesq Wave) model, MIKE 21 HD (Hydrodynamics) model and MIKE 21 ST (Sediment Transport) model were utilized to simulate wave, current, and sediment actions, respectively. Simulations were conducted to represent the wave conditions for each season, obtained from hindcast data within the study area. To compare the impact of the proposed harbor on the coastal processes, numerical simulation results were compared and analyzed both with and without harbor conditions.

In conclusion, the results of the numerical simulations support the suitability of the chosen harbor location and layout. Through the consideration of stakeholder requirements and a comprehensive understanding of coastal processes, the harbor design ensures secure navigation, optimizes hydrodynamic performance, and minimizes potential siltation issues. This study underscores the significance of accurately assessing coastal processes in the development of a harbor that enhances efficient fishing activities while mitigating adverse effects stemming from waves, currents, and sediments.

Acknowledgments

The authors wish to acknowledge the “Feasibility Study and Detailed Engineering Designs for Development of Fishery Harbour at Balapitiya Project” of MFARD (Ministry of Fisheries and Aquatic Resources Development) in Sri Lanka for their various support for the success of this research.

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CHANGE DETECTION FROM 2017-2022 OF MANGROVE AREA AROUND THAMPALAGAM BAY AND ESTIMATION OF CARBON DIOXIDE ABSORPTION OF MANGROVES IN A SELECTED AREA USING GIS AND REMOTE SENSING TECHNIQUES

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Abstract: Mangroves are extremely productive ecosystems along the coast that help to mitigate climate change by absorbing carbon dioxide from the atmosphere. Understanding variations in mangrove areas and carbon storage capacity is critical for assessing these ecosystems' resilience and vulnerability to climate change. This study aims to detect changes in the mangrove area around Thambalagamam Bay in Trincomalee, Sri Lanka, from 2017 to 2022, as well as to estimate carbon dioxide (CO_2) absorption by mangroves in an identified area using GIS and remote sensing techniques. The approach incorporates Sentinel -2 multispectral satellite images with a spatial resolution of 10m, as well as the mangrove vegetation index and supervised image classification algorithms. The approaches' accuracy is evaluated using ground truth data and the Google Earth Engine. The above-ground biomass measurements were calculated according to the allometric equations of mangrove species and above-ground carbon stock, and CO_2 absorption was calculated using empirical equations. The mangrove vegetation index (MVI) method gives mangrove forest areas of 12.03 km^2, 10.52 km^2, 8.05 km^2, 8.15 km^2, 10.63 km^2, and 7.77km^2 for the years from 2017 to 2022 respectively. The supervised classification using the maximum likelihood classifier (MLC) method gives the forest areas of 12.09 km^2, 10.61 km^2, 8.13 km^2, 8.20 km^2, 10.71 km^2, 7.81 km^2 for the years from 2017 to 2022, respectively. Both methods show a similar accuracy of over 90%. The extent of mangrove forests shows a decreasing trend from 2017 to 2019 and an increase from 2019 to 2021 which indicates potential recovery and successful conservation measures and again shows a sharp decrease from 2021 to 2022 indicating deforestation. Results of the polynomial regression analysis show NDVI had a strong correlation ($AGB = 7232 - 20420NDVI + 14482NDVI^2$; r^2 =92.10%) with above-ground biomass (AGB) in the Thambalagamam Bay mangrove forest. Increasing order of total absorbed CO_2 relevant to a stratum is *Luminetzera racemose* (186.195 ton/ha), Multispecies (439.858 ton/ha), *Rhizopora mucronate* (453.825 ton/ha), *Avicena officinalis* (675.937 ton/ha), *Avicena marina* (2635.572 ton/ha). A total, of 4391.387 tons/ha of CO_2 was absorbed by the selected site of mangrove forest around Thambalagam Bay. The study highlights the importance of efforts to preserve the long-term survival of mangrove ecosystems in the face of global climate change.

Keywords: Mangrove; Change detection; Above-ground biomass (AGB); CO_2 absorption; Climate change

1. Introduction

Mangrove forests are salt-tolerant evergreen species found along sheltered coastlines, shallow-water lagoons, estuaries, rivers, and deltas. They grow as tree shrubs according to the climate, the salinity of the water, topography, and edaphic features of the area (Huong et al.,2021). The highest mangrove diversity is found in Southeast Asia, with Indonesia having the largest mangrove forest area. Other countries with extensive mangrove forests include Bangladesh, Brazil, Nigeria, and Australia. Mangrove areas account for 0.7% of the total tropical forests in the world. The largest mangrove area was found in Asia (42.0%), followed by Africa (20.0%), North and Central America (15.0%), Oceania (12.0%), and South America (11.0%) (Giri et al.,2011). Mangrove vegetation found in Sri Lanka is considered highly diverse and more than 50% of the species exclusive to the Indo-West Pacific region is found in the country (Amarasinghe and Perera 2017). A study by Kathiresan and Bingham (2001) identified 21 mangrove species in Sri Lanka belonging to 13 genera. Mangrove forest patches are found throughout the coastal areas in Sri Lanka located in the Puttalam Lagoon in the west, Batticaloa Lagoon and Trincomalee in the east (Giri et al.,2015). Mangroves in Sri Lanka as being discontinuously distributed along the coast around lagoons, bays, and estuaries covering an area of 15,670 ha (Ranawana et al.,2017). Giri et al. (2011) highlighted the importance of using remote sensing techniques for change detection in mangroves. The study found that remote sensing techniques such as Landsat imagery and aerial photography can be used to accurately map and monitor changes in mangrove ecosystems over time. Mangroves are important carbon sinks that play critical roles in mitigating climate change. Donato et al. (2011) estimated that mangroves sequester an average of 0.7 metric tons of carbon per hectare per year, which is much higher than that of other terrestrial ecosystems. Mangroves provide habitat for a wide range of species, including many commercially important fish and shellfish species. According to Dahdouh-Guebas et al. (2005), mangroves provide habitats for over 50 species of fish and 20 species of crabs. Mangroves are natural coastal barriers that protect against storm surges, tsunamis, and erosion. Kathiresan and Rajendran (2005) estimated that mangroves could reduce the energy of waves by up to 66%. Mangrove forests support some of the world's most productive fisheries. According to Polidoro et al. (2010), mangroves are important spawning and nursery areas for many commercially valuable fish species, including snappers, groupers, and barramundi. Mangroves provide valuable wood and non-timber forest products that are important for local communities. According to Duke et al. (1998), mangroves provide wood for construction and fuel, as well as non-timber forest products such as honey, tannins, and medicinal plants. As with all other natural ecosystems, mangrove forests in Sri Lanka provide many extractive and non-extractive uses for the benefit of mankind. However, many extractive uses, such as shrimp culture and house construction, cause extensive damage to forests. In addition, increasing the utilization of resources severely affects its stability. Aboveground biomass is an important carbon pool in mangrove ecosystems (Howard et al.,2014). Importantly, mangroves are efficient carbon sinks because they sequester carbon in their above- and below-ground biomass as well as in their sediments (Pham and Yoshino, 2018). The traditional approach to field biomass estimation of mangroves is limited by the spatial constraints of data collection and the inaccessibility of mangrove stands. A common non-destructive approach is the use of allometric equations derived from parameters such as diameter at breast height (DBH). Remote sensing serves as a non-destructive alternative for robust, continuous, and spatially explicit biomass assessment (Herold and Johns, 2007). CO2 absorption is essential to mitigate climate change by reducing the amount of greenhouse gases in the atmosphere. A study by Sabine et al. (2004) found that ocean and land ecosystems absorb approximately half of the CO2 emitted by human activities. CO2 absorption plays an important role in maintaining the ecosystem balance. According to Lovett et al. (2016), increasing CO2 levels can have significant impacts on plant growth and ecosystem dynamics, which can have cascading effects on other organisms in the ecosystem. CO2 absorption can provide significant economic benefits by reducing the costs associated with climate change. CO2 absorption plays an important role in supporting biodiversity by maintaining the ecosystem balance. An allometric equation is constructed by developing a relationship between the amount of biomass or carbon from the destructive sampling and forest parameters, such as diameter at breast height (DBH), tree height, and wood density. (Tyas Mutiara Basuki et al.,2022). It is an important tool for estimating tree weight from independent variables such as trunk diameter, tree height, crown height, and total height that are easily measurable in the field. The growth rate of one part of the tree is proportional to that of others, which is the basic concept of the allometric relationship and therefore the trunk diameter of a tree is highly correlated with trunk weight (Komiyama et al.,2008). Allometric equations are essential to accurately estimate the biomass and carbon stocks of trees and forests. Allometric equations provide a standardized method for measuring tree and forest characteristics, making it easier to compare data across different studies and regions. Satellite data analysis, along with a geographical information system (GIS), is the most important method for regularly monitoring mangrove ecosystems. GIS and remote sensing technologies can be used to monitor the health of mangrove ecosystems, including changes in the vegetation structure and biomass. Ouma et al. (2020) found that remote sensing data can be used to monitor changes in vegetation structure and biomass in mangroves, providing valuable information for ecosystem management. In-situ observations provide the most accurate information on mangroves. However, collecting in situ observation through field surveys is challenging due to the limited accessibility of mangrove communities, as they are located in harsh and tidally inundated environments (Zhao, C and Qin, C-Z,2020). Lin et al. (2014) found that remote sensing data can be used to detect changes in mangrove cover cost-effectively, particularly in areas with limited accessibility.GIS and remote sensing technologies provide a reliable and accurate way of mapping mangrove extent. Aslan et al. (2019) found that remote sensing data can be used to accurately map the extent of mangroves, even in areas with complex topography. Regarding the role of remotely sensed data, the effect of input features is a key component in image classification. Many mangrove studies have been conducted using optical images of different resolutions (e.g., IKONOS, QuickBird, WorldView-3, Landsat series, and SPOT), synthetic aperture radar (SAR) data, and airborne hyperspectral data (Yoshino, K et al., 2019) (Wang, L.;Sousa et al.,2004). The launch of the sentinel-2 satellites by the European Space Agency in 2015 provided a valuable opportunity for the remote sensing community to develop classification approaches in various fields (Astola et al.,2019). GIS and remote sensing can be used to detect changes in mangrove cover over time, thereby providing valuable information for monitoring and conservation purposes. Saenger et al. (2002) found that remote sensing data can be used to detect changes in mangrove cover with a high degree of accuracy. Thus, global warming has become a global issue. This has led to climate change due to an increase in greenhouse gas emissions. Greenhouse gases occur owing to the accumulation of carbon in the atmosphere (Griggs, 2002). Mangroves are also the largest reservoir of carbon, which plays a particularly important role in balancing O2 and atmospheric CO2, so they have a great influence on the climate of each country and region and greatly affect the temperature of the Earth through the regulation of greenhouse gases, especially CO2.The study aims to develop mangrove area maps around Thambalagam Bay from 2017 to 2022 using the Mangrove vegetation index(MVI) and Maximum Likelihood classification (MLC). To estimate Above-Ground Biomass (AGB), above-ground carbon stock (AGC), and total absorbed carbon dioxide by the mangrove forest in the selected site of Thambalagam Bay.

2. Data and Methods

Study area

Mangrove areas around Thambalagam Bay are located on the Western side of the bay in Trincomalee. The study area is roughly 52.57 km², 8.49578°N 81.14612°E, consisting of the Divisional secretariats division (DSDs) of Thambalagamam and Kinniya.

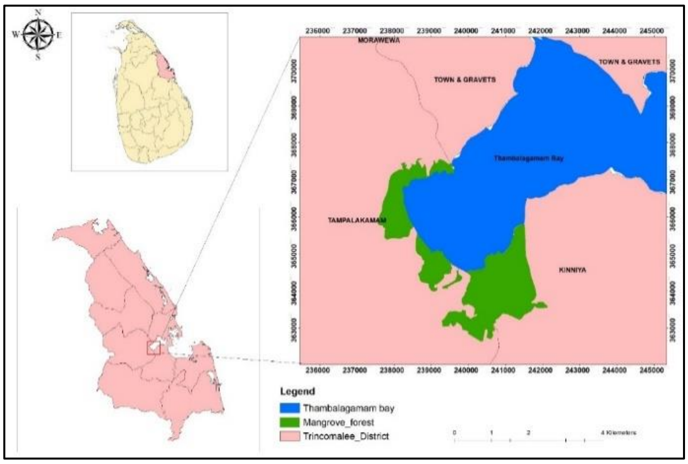

Figure 1:Study area - Thambalagam Bay.

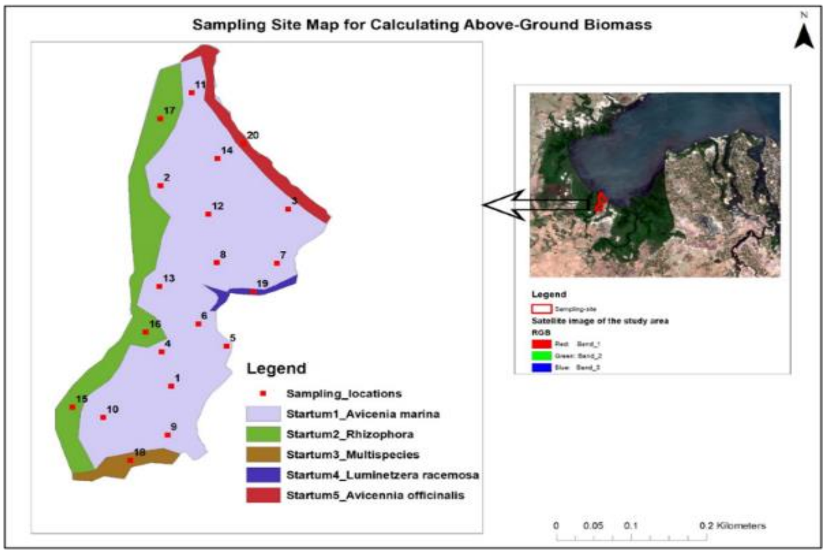

Figure 2:Sampling plots for each stratum for Above-Ground Estimation.

Data collection

Administrative boundary shape files with the country, province, district, divisional secretariat division (DSD), and Grama Niladhari divisions (GNDs) were obtained from the survey Department in Colombo. The surface reflectance images of Sentinel-2A and Sentinel-2B were retrieved directly through the Land Viewer satellite observation imagery tool from the Earth Observing System (EOS) website (https://eos.com/landviewer/). Because the study used the 20 m resolution SWIR1(B11), they had to be resampled to bring them to the 10m with blue (B2), green (B3), red (B4), and NIR (B8). Mangrove vegetation index and supervised classification methods were used to identify and map mangrove vegetation using Sentinel 2 images for years 2017, 2018, 2019, 2020, 2021, and 2022. ArcMap 10.8 software was used to analyze the images.

Mangrove mapping and Change detection

All the images were downloaded and subjected to the Mangrove vegetation index and supervised classification method, and the accuracy of each method was assessed using the Google Earth Engine and ground truth data. The methods are Supervised classification- (Maximum Likelihood Classifier) and Mangrove Vegetation Index. Accuracy assessment is mandatory in remote sensing data processing. It verifies the authenticity of the data provided to a user. Accuracy for the derived maps in each year (2017 to 2021) by the Mangrove vegetation index and supervised classification method was assessed using the Google Earth timeline reference maps as ground truth data. 300 of the ground truth-based pixel values were used for accuracy assessment (Rajendran et al.,2020). In this work, users, producers, and overall accuracies, together with kappa statistics, were derived from the error matrix (Science et al.,2021). Furthermore, a field survey was undertaken to collect training samples. 300 training samples were taken from the study area using rugged handheld GPS to assess the accuracy of each method. Using those training samples, accuracy values for the maps derived for 2022 were obtained. The post-classification change detection algorithm determined the vegetation change from the five classified images. It consisted of a statistical analysis and a comparative analysis of the variability of classified vegetation in the study area for each interval, for instance, the change that occurred during 2017-2018, 2018-2019, 2019-2020, 2020-2021, and 2021-2022.

Estimation of Above-ground biomass & CO_2 absorption

The purposive sampling method was used to select a site from the mangrove forest around Thambalagam Bay based on the ease of access. A field survey was carried out in the selected site to identify the mangrove species, and biodiversity indices were developed to find the species distribution and dominance. Diversity indices like species richness and evenness determine species dominance. The site was divided into five strata based on the species' dominance and named according to the dominant species. The five stratas are Avicenia marina, Rhizophora, Multispecies, Luminetzera racemose, Avicenia officinalis. The fishnet tool divided each stratum into grids (10m×10m). Twenty sampling plots were taken. Simple random sampling is used to select sampling grids. In each grid, trees below 1.5 m in height and dead trees are neglected, and all other tree species are considered. For all trees except Rhizophora sp, the Diameter at breast height (DBH) (above 1.3m) was measured using a Diameter tap, and species types were recorded. DBH was measured 30 cm above the highest prop root for Rhizophora sp. AGB was calculated using allometric equations of each mangrove species in each grid. Finally, calculate the total AGB of mangrove forest in the selected site in Thambalagam Bay as (ton/ha). Diameter tape is specially designed to convert the tree circumference to tree diameter, giving diameter directly. Using the diameter tape and starting from the ground, 1.3m was measured (=average breast height) up the tree trunk. The tree's circumference was measured by wrapping the measuring tape around the trunk at 1.3m. The reading was recorded, and the diameter was calculated (Watt & Donoghue,2005). Using the total AGB of mangrove forest in the selected site of Thambalagam Bay, AGC was calculated using equation 10 by a raster calculator.
The equation used to calculate AGC was,

$$\mathrm{AGC} = \mathrm{AGB} \times 0.47 \ldots\ldots\ldots\ldots\ldots \text{(Howard et al.,2014)} \quad \text{(Equation 1)}$$

Using the total AGC of the mangrove forest in the selected site of Thambalagam Bay, total absorbed CO2 was calculated using equation 11 by a raster calculator.
The equation used to calculate total absorbed CO2 was,

$$\text{Total O2 absorbed} = \mathrm{AGC}\ (\mathrm{ton/ha}) \times 44/12 \ldots\ldots\ldots\ldots\ldots\ldots \text{(Equation 2)}$$
$$\text{(Eggleston et al.,2006)}$$

3 Results and Discussion

The global distribution of mangroves is affected by both anthropogenic and natural factors. Anthropogenic factors, including coastal development, agriculture, aquaculture, and logging, have led to the loss and degradation of mangrove forests. Natural factors, including storms, tsunamis, and sea-level rise, can also have a significant impact on mangrove ecosystems. When mapping mangrove forests around Thambalagamam Bay using the Maximum likelihood method and the Mangrove vegetation index method, both methods gave over 90% accuracy. However, there is a slight difference between the mangrove extents classified by these two methods. The mangrove vegetation index can be attributed to its ability to capture the specific spectral properties of mangrove vegetation. The mangrove vegetation index encompasses the Green band, NIR band, and Short wave infrared band (SWIR). In plants, mesophyll cells in the leaves reflect NIR but the amount of reflection is different for mangroves. Here the internal cell structure is recognized by NIR part and moisture is recognized by SWIR therefore, this index takes into account the unique reflectance characteristics of mangroves allowing for a more targeted and precise classification. This approach enhances the ability to discriminate between mangrove forests and other land cover types, resulting in higher accuracy. A recent study by Jayatissa et al. (2018) assessed the distribution of mangroves in Sri Lanka using high-resolution satellite imagery. The study found that the total mangrove area in Sri Lanka declined by 16% between 1990 and 2015, with the highest rates of deforestation occurring in the western and southern regions of the country. This study also found that small-scale deforestation for firewood production and aquaculture was the main driver of mangrove loss in Sri Lanka. A more recent study by Senarathne et al. (2021) investigated the impact of anthropogenic activities on the distribution of mangroves in Thambalagam Bay. This study found that the total area of mangroves in the bay declined by 23.3% between 2009 and 2019, with the highest rates of deforestation occurring in areas adjacent to human settlements and aquaculture ponds. This study also highlighted the need for effective management strategies to mitigate the impact of anthropogenic activities on mangrove ecosystems in Thambalagam Bay.

Derived maps were given more than 90% overall accuracy.

Table 1: Summary Table of Classification accuracy test from 2017-2022.

Mangrove mapping methods	**Overall accuracy% and Kappa Coefficient**						**Mean±SD**
	2017	2018	2019	2020	2021	2022	
Supervised classification (MLC)	92.56 0.91	93.22 0.92	92.33 0.91	93.39 0.92	93.4 0.93	93.6 0.92	93.08±0.51 0.92
Mangrove Vegetation Index (MVI)	94.66 0.92	94.33 0.91	95 0.93	96.33 0.94	93 0.90	95 0.93	94.72±1.08 0.92

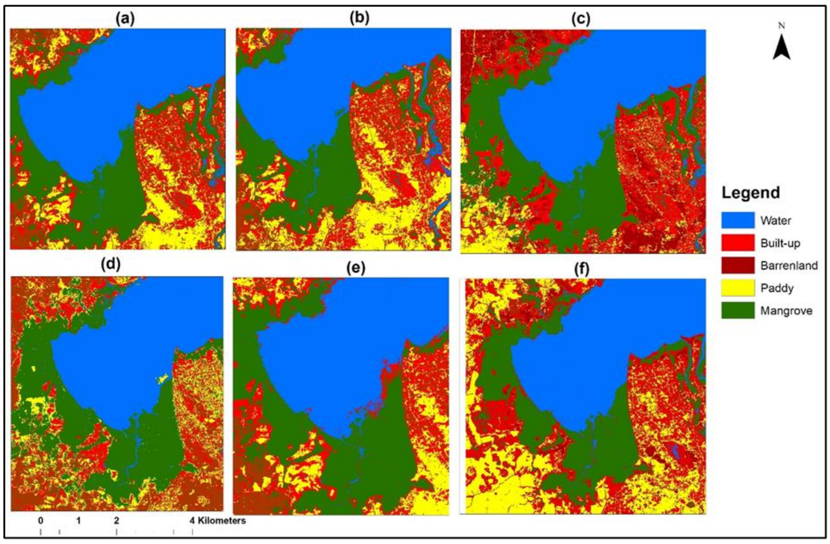

Figure 3: Derived maps through the supervised classification (MLC) method (a) 2017 (b) 2018 (c) 2019 (d) 2020 (e) 2021 (f) 2022.

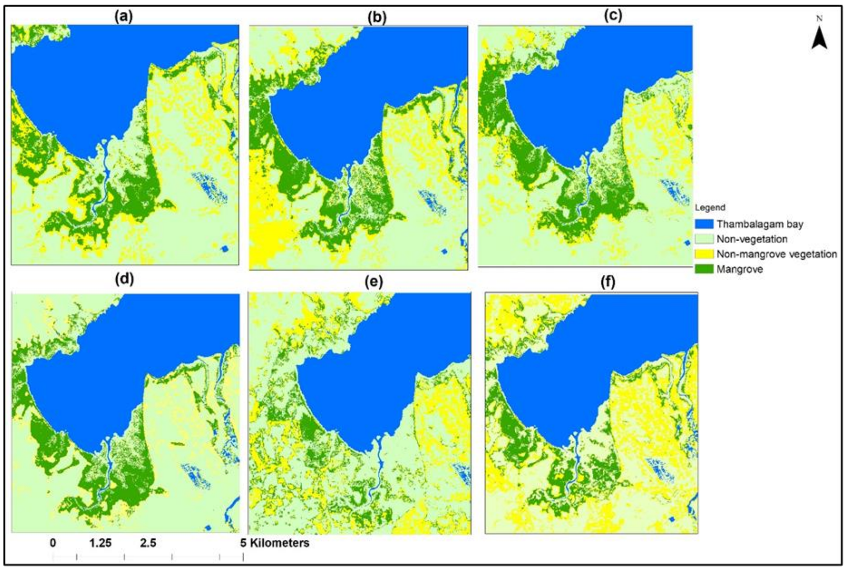

Figure 4: Derived maps through the mangrove vegetation index (MVI) method (a) 2017 (b) 2018 (c) 2019 (d) 2020 (e) 2021 and (f) 2022.

When considering the mangrove extent obtained through the supervised classification using the MLC method, in 2017, its value was 12.09km2, and followed by 2018 to 2022 was 10.61 km2, 8.13 km2, 8.20 km2, 10.71 km2, 7.81 km2 respectively.

The area covered by water remains constant. The mangrove area extent has fluctuated over the past six years, overall showing a decline. The area under paddy cultivation has shown slight fluctuations over the past six years it increased from 8.86 km2 in 2017 to 9.49 km2 in 2021 before slightly decreasing to 8.97 km2 in 2022. But the area covered by built-up land has consistently increased over the years. It rose from 10.11 km2 in 2017 to 16.02 km2 in 2022. Barre land area also shows fluctuations and there was a sharp decline to 0.25 km2 in 2022.

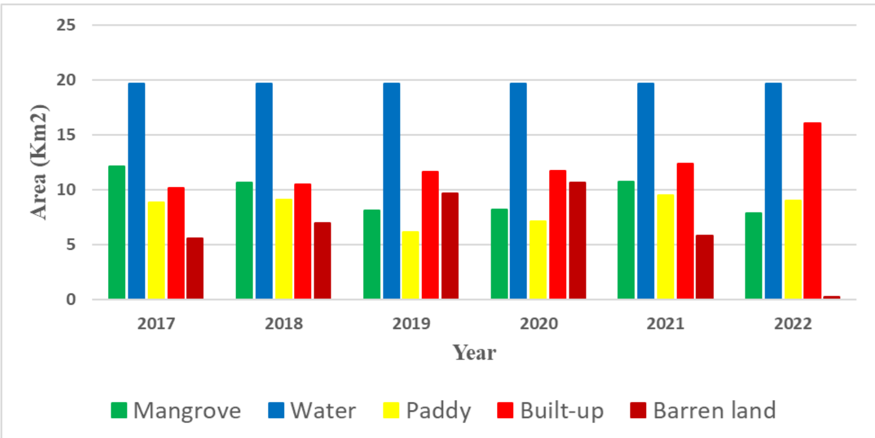

Figure 5: Area extent of the classified classes through the supervised MLC classification methods.

Table 2: Area extent of the classified classes through the supervised MLC classification method from 2017 to 2022.

Land use	Area extent (Km^2)					
	2017	2018	2019	2020	2021	2022
Mangrove	12.09	10.61	8.13	8.2	10.71	7.81
Water	19.71	19.71	19.71	19.71	19.71	19.71
Paddy	8.86	9.09	6.12	7.13	9.49	8.97
Built-up	10.11	10.51	11.63	11.7	12.33	16.02
Barren land	5.52	6.97	9.63	10.6	5.83	0.25

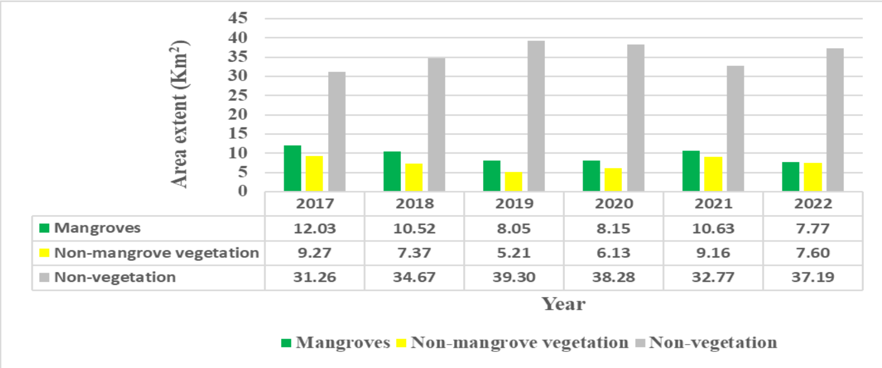

Figure 6: Area extent of the classified classes through the mangrove vegetation index (MVI) classification method in the year from 2017 to 2022.

Out of the total extent of the study area of 52.57 km2, the mangrove extent obtained through the “Mangrove Vegetation Index (MVI)”, from 2017 to 2022 is 12.03 km2, 10.52 km2,8.05 km2,8.15 km 2,10.63 km2,7.77 km2 respectively. Non-mangrove vegetation (paddy and other crops) decreased from 9.27 km2 in 2017 to 5.21 km2 in 2019, followed by a slight decrease in 2022. Non-vegetation (water, built-up, barren land) shows fluctuations over the past six years. It increased from 31.26 km2 in 2017 to 39.30 km2 in 2019, indicating land transformation.

Table 3: Area extent of the classified classes through the mangrove vegetation index (MVI) classification method in the years from 2017 to 2022.

Land use	Area extent (Km^2)					
	2017	2018	2019	2020	2021	2022
Mangroves	12.03	10.5	8.05	8.15	10.63	7.77
Non-mangrove vegetation	9.27	7.37	5.21	6.13	9.16	7.60
Non-vegetation	31.26	34.67	39.30	38.28	32.77	37.19

Overall, the extent of mangrove forests has been subjected to a decreasing trend within the four years, from 2017 to 2022.

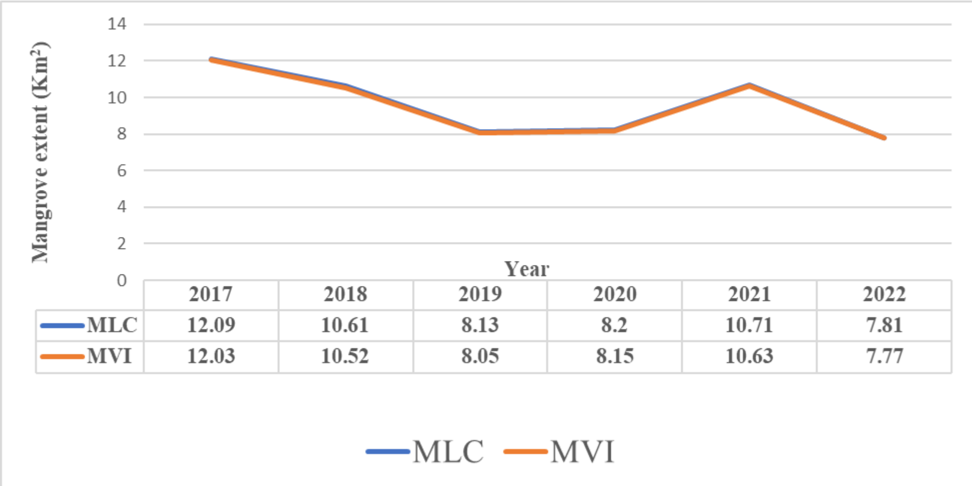

Figure 7: Mangrove extent data obtained from supervised (MLC) and MVI methods.

According to the graphs (Figure 7), overall, the extent of mangrove forest has been subjected to a decreasing trend within the four years, from 2017 to 2022. The change detection results obtained from both the maximum likelihood classification and mangrove vegetation index method can provide valuable insights into the trend of mangrove extent change over time. According to the Maximum likelihood method, there was a significant 12.21% decrease in mangrove extent from 2017 to 2018. This decrease was also reflected in the mangrove vegetation index method, which showed a decline of 12.55% during the same period. In 2018-2019, both methods showed a decrease, with a decline of 23.37% in the maximum likelihood method and 23.47% in the mangrove vegetation index method. This could indicate a potential threat to the mangrove ecosystems in this area. This period was characterized by natural disturbances, such as cyclones or other climate-induced events that could have affected the mangrove ecosystem. In 2019-2020, the Maximum Likelihood method showed an increase of 0.86% in mangrove extent, whereas the mangrove vegetation index method also showed an increase of 1.24%. Further, in 2020-2021, there was a significant increase of 30.6% in mangrove extent according to the maximum likelihood method, similarly, the mangrove vegetation index method showed an increase of 30.4%. This increase could be due to conservation and restoration efforts or natural regrowth of the mangrove forest. Finally, in 2021-2022, the maximum likelihood method showed a decline of 27.07% in mangrove extent, whereas the mangrove vegetation index method showed a decline of 26.9%. The reasons for this sudden decline may be due to increasing deforestation activities by local people of neighboring areas to extract valuable wood resources for their livelihood, cattle grazing, Land encroachment and changes in land use patterns, etc. In summary, both the maximum likelihood classification and mangrove vegetation index method showed fluctuations in mangrove extent over the past six years. This information can be used to inform conservation and management efforts for mangrove ecosystems in the area. In addition, land use classification results provide valuable insights into the changes in land use in the region over the past six years. It shows both positive and negative trends in different land use categories, which can be crucial for sustainable land management and urban planning. The decline in mangrove areas in recent years indicates potential threats to these ecologically valuable habitats. Policymakers and conservationists should take proactive measures to protect and restore mangrove ecosystems to ensure their ecological and socio-economic benefits. Other than mangroves, the stable area in waterbodies is a positive sign. Fluctuations in paddy cultivation areas may indicate changing agricultural practices or land-use decisions. Agricultural policies should aim for sustainable farming practices to ensure food security while minimizing negative environmental impacts. The consistent increase in built-up areas reflects urban expansion therefore sustainable urban planning is necessary to manage urban growth while preserving the mangrove ecosystem around Thambalagamam Bay. The decline in barren land area in 2022 indicates efforts in land reclamation. Understanding the reasons behind this change can help guide land-use planning and improve resource management.

Table 4: Change detection percentage of mangrove areas around Thambalagam Bay obtained by the supervised classification MLC and MVI methods in the year between 2017-2022.

Year	**Mangrove area change (%)**	
	MLC method	**MVI method**
2017-2018	**-12.21**	**-12.55**
2018-2019	**-23.37**	**-23.47**
2019-2020	**+0.86**	**+1.24**
2020-2021	**+30.6**	**+30.4**
2021-2022	**-27.07**	**-26.9**

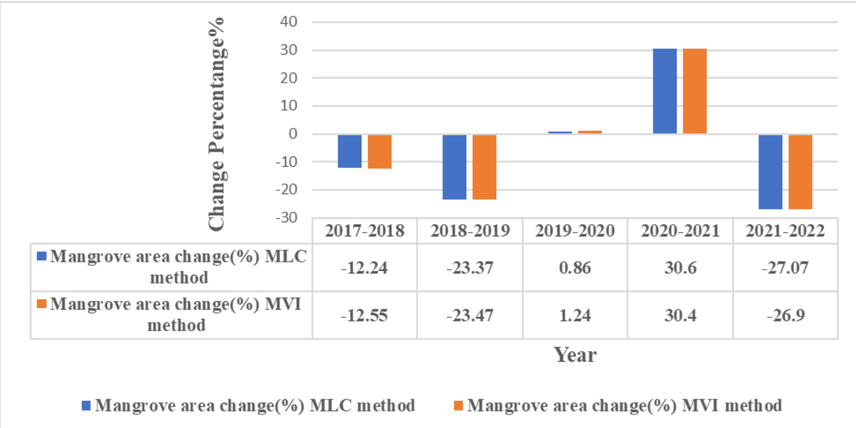

Figure 8: Change detection percentage of mangrove areas around Thambalagam Bay obtained through the supervised classification (MLC) and MVI in the year 2017-2022.

Table 5: Summary Table for estimated biodiversity indices in each stratum.

Stratum	**Dominant species**	**Species richness**	**Shannon-Weiner index**	**Evenness**	**Simpson index**
1	*Avicenia marina*	1			
2	*Rhizopora apiculate*	10	1.339	0.581	0.579
3	*Rhizopora apiculate* and *Brugira gymnorhyza*	8	1.885	-0.194	0.832
4	*Luminetzera racemosa*	2	0.450	0.225	0.283
5	*Avicenna officinalis*	9	1.487	0.677	0.685

The field survey results give important insights into the vegetation composition and ecological aspects of the mangrove forest in Thamabalagam Bay. The dominating species, species richness, diversity indices, and evenness vary over the (Stratum 1-5). *Avicenna marina* dominates Stratum 1, with a total of 1060 trees counted. This suggests that this species has a high dominance in this stratum. *Rhizopora apiculata* develops as the dominating species in Stratum 2. The number of species is ten, suggesting the presence of a diversified plant ecosystem. The Shannon-Weiner index of 1.339 shows moderate variety, while the evenness value of 0.581 indicates an even distribution of individuals among species. The Simpson index of 0.579 indicates that species dominance is balanced. Moving on to Stratum 3, the main species are *Rhizopora apiculata* and *Brugira gymnorhiza*. When compared to Stratum 2, the species richness drops to 8, suggesting a little lesser diversity. However, the Shannon-Weiner score rises to 1.885, suggesting greater diversity. Surprisingly, the evenness number is given as -0.194, raising questions about the data's veracity or probable calculation flaws. The Simpson index of 0.832 indicates that certain species have a rather high dominance within this stratum. The dominating species in Stratum 4 is *Luminetzera racemosa*. The species richness falls dramatically to 2, indicating a lower level of variety in this strata. The Shannon-Weiner score falls to 0.451, showing less diversity than in prior layers. The evenness rating of 0.225 indicates that people are distributed very evenly across the few species present. The Simpson index of 0.284 shows a level of dominance that is moderate. Finally, *Avicenna officinalis* dominates Stratum 5. Unfortunately, no information on species richness is available, which limits our knowledge of the total diversity in this stratum. The Shannon-Weiner index of 1.487, on the other hand, implies very great variety, while the evenness value of 0.677 indicates a generally even distribution of individuals among species. The Simpson index of 0.685 suggests that this stratum has a balanced preponderance of species. Overall, the results show differences in dominating species, species richness, diversity indices, and evenness across strata. Straum 2 has a reasonably high amount of diversity, but Stratum 3 has a larger level of diversity but may have calculation mistakes in evenness. Stratum 4 and 5 have lower levels of species richness, variety, and dominance. These findings can help us comprehend the vegetation structure and biodiversity trends in the selected site of the mangrove forest around Thambalagam Bay. However, additional research and data are required to accurately understand the ecological relevance and conservation implications of these various strata.

Table 6: Summary Table for Above-ground biomass, Above-ground carbon stock, and CO_2 absorption for stratums in the selected site of the mangrove forest in Thambalagam Bay.

Stratum	**AGB(ton/ha)**	**AGC(ton/ha)**	**Total CO2 absorbed (ton/ha)**
(Stratum1)*Avicenna marina*	**1529.206**	**718.727**	**2635.572**
(Stratum2)*Rhizopora mu-cronata*	**263.3178**	**123.7594**	**453.825**
(Stratum3)Multispecies	**255.214**	**119.95**	**439.8587**
(Stratum4)*Luminetzera rac-emosa*	**108.0337**	**50.775**	**186.195**
(Stratum5)*Avicena offici-nalis*	**392.191**	**184.329**	**675.937**

The aboveground biomass (AGB) values for different strata of mangroves in tons per hectare (ton/ha) are as follows: Stratum 1 *Avicena marina*, 1529.206 ton/ha; Stratum 2 *Rhizopora mu-cronata*, 263.3178 ton/ha; Stratum 3 multispecies, 255.214 ton/ha; Stratum 4 *Luminetzera racemosa*, 108.0337 ton/ha; Stratum 5 *Avicena officinalis*, 392.191 ton/ha. AGB values are important indicators of the carbon storage potential of mangrove forests. The stratum1 *Avicen-*

na marina, which has the highest AGB value (1529.206 ton/ha) among the strata, is known to be a highly productive species and has been reported to have high carbon storage potential. The stratum 2 *Rhizopora mucronata*, on the other hand, has a relatively low AGB value (263.317 tons/ha), which is in line with its slow growth rate and low carbon storage potential. The stratum 3 and stratum 4 *Luminetzera racemosa* strata had AGB values in the intermediate range. However, the stratum4 *Luminetzera racemosa* (108.033 ton/ha) had a relatively lower AGB value, which could be due to its smaller structure and slower growth rate compared to other species. Stratum 5 *Avicena officinalis* has a higher AGB value than Stratum 4 *Luminetzera racemose* but lower than that of Stratum 1 *Avicena marina*. It is a common species found in mangrove forests and has a moderate carbon storage potential. The total Aboveground biomass of the selected site of mangrove forest around Thambalagam Bay is 2547.963 tons/ha. Overall, AGB values provide valuable information on the biomass and carbon storage potential of different mangrove species, which is important for the management and conservation of these ecosystems. The aboveground carbon stock (AGC) is an important metric for estimating the carbon sequestration potential of different vegetation types. The above-ground carbon stock values obtained for different vegetation strata can help us understand the contribution of each stratum to the total carbon stock of the ecosystem. In this case, we have aboveground carbon stock values for five different vegetation strata. The highest carbon stock value was obtained for stratum1 *Avicena marina*, with a value of 718.727 tons/ha. This indicated that stratum1 *Avicena marina* is a highly carbon-rich species and plays an important role in carbon sequestration. The second-highest carbon stock value was obtained for stratum 3, with a value of 119.95 tons/ha. This suggests that the presence of multiple species in the ecosystem contributes to higher carbon sequestration potential. Stratum 2 *Rhizopora mucronata*, Stratum 4 *Luminetzera racemosa*, and stratum 5 *Avicena officinalis* have lower carbon stock values than Stratum 1 *Avicena marina* and stratum 3. However, their contribution to the total carbon stock of the ecosystem should not be overlooked because every stratum of vegetation plays a role in carbon sequestration. Overall, the aboveground carbon stock values obtained for different strata of vegetation provide important information about the carbon sequestration potential of the ecosystem. This information can be useful for the conservation and restoration, and management of mangrove ecosystems as well as for climate change mitigation efforts. Every year, approximately 100 billion tons of CO_2 is fixed by photosynthesis carried out by trees, and a similar amount is returned to the atmosphere by the respiration of the organism. According to Donato et al. (2011), mangroves have the potential to sequester up to 4.2 billion metric tons of CO_2 globally, which is equivalent to the annual emissions of approximately 1 billion cars. A study by Alongi et al. (2016) estimated that mangroves sequester an average of 2.6 metric tons of CO_2 per hectare per year. However, sequestration rates can vary depending on factors such as temperature, salinity, and nutrient availability.

The total absorbed CO_2 in different strata can provide insights into the carbon sequestration potential of different plant species. In this case, Stratum1 *Avicena marina* had the highest absorbed CO_2 value of 2635.572 tons/ha, indicating that this species has a high carbon absorption potential. Stratum 2 *Rhizopora mucronata*, Stratum 3 multispecies, and Stratum 5 *Avicena officinalis* also had considerable carbon absorption potential, with absorbed CO_2 values of 453.825 ton/ha, 439.858 ton/ha, and 675.937 ton/ha, respectively. On the other hand, Stratum 4 *Luminetzera racemosa* had the lowest absorbed CO_2 value of 186.195 tons/ha, suggesting that this species has a lower carbon absorption potential than other species in the area. Total, of 4391.387 tons/ha of CO_2 was absorbed by the selected site of the mangrove forest around Thambalagam Bay. Overall, the absorbed CO_2 values for different strata can help us understand the role of different plant species in mitigating climate change by absorbing and sequestering carbon from the atmosphere. It is important to consider the carbon sequestration potential of different species when designing and implementing afforestation and reforestation projects.

Table 7: Summary table of Vegetation indices and Above-ground biomass, Above-ground carbon stock, and CO_2 absorption for stratums in the selected site of the mangrove forest in Thambalagam Bay.

Plot number	NDVI	SAVI	GNDVI	RVI	AGB(ton/ha)	AGC(ton/ha)	CO_2(ton/ha)
1	0.8024	0.5548	0.4707	3.2065	147.7186	69.4277	254.5915
2	0.7416	0.4995	0.4087	2.8483	65.8297	30.9399	113.4568
3	0.7859	0.5458	0.4687	3.2016	125.5211	58.9949	216.3343
4	0.8070	0.5711	0.4731	3.2212	158.4591	74.4757	273.1025
5	0.7701	0.5241	0.4311	3.0599	102.1136	47.9933	175.9917
6	0.7614	0.5104	0.4263	2.9933	91.0900	42.8123	156.9927
7	0.7774	0.5359	0.4487	3.1366	110.9717	52.1566	191.2586
8	0.7724	0.5311	0.4391	3.1178	107.0643	50.3202	184.5242
9	0.7805	0.5442	0.4531	3.1961	117.4926	55.2215	202.4973
10	0.7724	0.5337	0.4435	3.1279	109.8021	51.6069	189.2428
11	0.7525	0.5097	0.4131	2.9424	77.5813	36.4632	133.7107
12	0.7350	0.4915	0.3941	2.6840	63.1440	29.6777	108.8281
13	0.7925	0.5449	0.4683	3.1366	125.2287	58.8574	215.8304
14	0.7977	0.5468	0.4691	3.1961	127.1895	59.7790	219.2098
15	0.8516	0.5785	0.4691	2.9971	101.0297	47.4839	174.1237
16	0.8278	0.5416	0.4407	2.9971	83.9805	39.4708	144.7395
17	0.7973	0.4852	0.4275	2.7514	78.3076	36.8045	134.9623
18	0.7688	0.5141	0.4399	2.7889	255.2140	119.9505	439.8587
19	0.6493	0.4625	0.4029	2.2936	108.0337	50.7758	186.1950
20	0.6557	0.4137	0.4407	2.7481	392.1910	184.3297	675.9372

When considering the relationship between measured above-ground biomass and vegetation indices values it is showing a non-linear relationship. Therefore, polynomial regression analysis has been conducted to derive an equation between the dependent variable (Above-ground biomass) and independent variable (vegetation indices). According to the polynomial regression analysis results for NDVI, SAVI, GNDVI and RVI, the highest values of R^2 value observed for the NDVI model, which is 92.10%. This indicates that the NDVI model explains a larger proportion of the variation in AGB compared to other models. Also, when comparing the measured above-ground biomass with the NDVI model predicted Above-ground biomass at a 95% confidence level the predicted and measured AGB values are almost the same (p=0.983 >0.05). Similar polynomial relationships were found in previous studies. A study by G.Bindu et al.,2018 established a model between AGB and NDVI where the non-linear regression provides the best estimate of AGB for the NDV da with relatively high r^2value (0.710) with a model equation $AGB = 0.507e^{(NDVI*9.933)}$. Also, a study by F.F.Muhsoni et al.,2017 comparing different sentinel-2 derived etation indices found a polynomial lationship between NDVI and Mangrove bio-mass, $Y = 0.0316e^{22.26x}$ with r^2 value (0.859) and $Y = 86773x^2 - 62664x + 11397$ with r^2 value (0.814). Also, a study by Sendi Yusandi et al.,2018alund that a exponential relationship between AGB and NDVI, $B = 0.0023404e^{(20*NDVI)}$ with the r^2value (0.771).

Table 8: Summary of polynomial regression models using above-ground biomass and vegetation indices.

Vegetation Index	Model	r^2	Adjusted r^2	S
NDVI	$AGB = 7232 - 20420NDVI + 14482NDVI\wedge 2$	92.10%	91.10%	22.28
SAVI	$AGB = 4362 - 18502SAVI + 19800SAVI\wedge 2$	78.00%	75.40%	37.13
GNDVI	$AGB = 7087 - 34067GNDVI + 41341GNDVI\wedge 2$	55.80%	50.60%	52.65
RVI	$AGB = 2566 - 1945RVI + 375.7RVI\wedge 2$	47.30%	41.10%	57.47

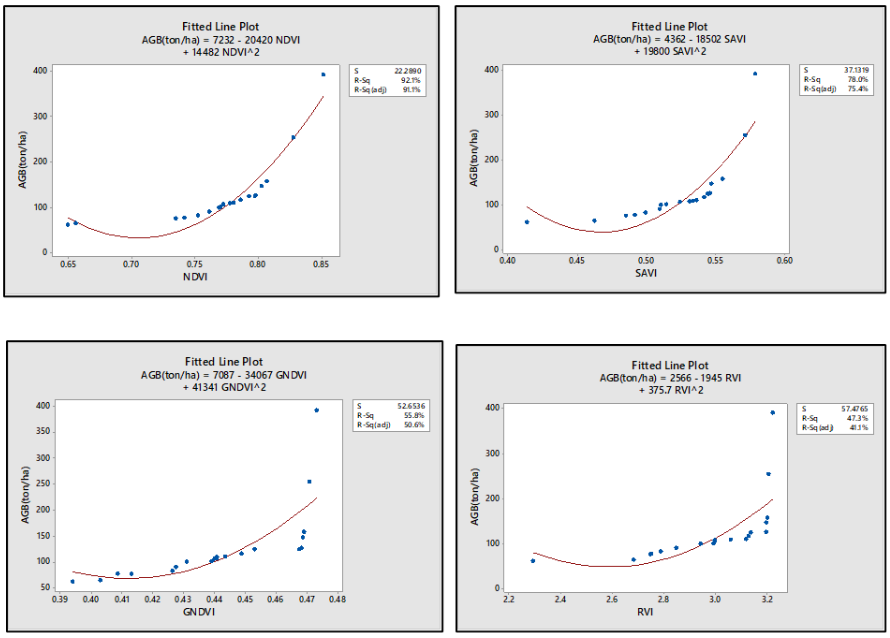

Figure 9: Scatterplots of correlations between aboveground biomass (AGB) and Vegetation indices (a)NDVI (b)SAVI (c)GNDVI (d)RVI.

Accurate mapping of mangroves presents various difficulties. When mangrove species are mixed with other species that have identical characteristics, the number of bands in the sensor can often make it difficult to distinguish between the various species. Furthermore, it might be highly challenging to find remote sensing data for a certain area and time. Particularly for long-term analyses like change detection, several years of data are essential, which is occasionally not attainable with only one sensor's data. The classification of mangrove species using high spatial resolution data, such as hyperspectral and LiDAR, is effective, but it is difficult due to the high cost of data collecting, limited availability of spatial data, and the large storage needs. The tidal influence on mangrove areas is also a significant concern since it alters the spectral signature of mangroves and has an impact on a number of remote sensing parameters used to assess mangroves. Analyzing long-term changes in mangrove forests, precise estimations of above-ground biomass, and carbon dioxide absorption studies all need careful consideration of the underlying challenges.

3. Conclusion

1. The mangrove extent has fluctuated from 2017 to 2022, and the values derived using the maximum likelihood classifier and mangrove vegetation index method differ significantly ($p<0.05$).

2. The change detection results also showed that the mangrove extent around Thambalagam Bay decreased in 2017-2019 by 36.02% and increased in 2020-2021 by 30.4% again decreasing in 2021-2022 by 26.9%.

3. NDVI was the best predictor of the Above-ground biomass of the Mangrove Forest around Thambalagam Bay with a 92.10% coefficient of determination (R^2).

4. There is no significant difference between the predicted AGB and Measured AGB values ($p>0.05$). Therefore Above-ground Biomass predicted using NDVI is very close to the measured Above-ground Biomass using allometric equations in the Mangrove Forest around Thambalagam Bay.

5. Overall, 4391.387 ton/ha CO_2 was absorbed by the selected site of mangrove forest around Thambalagam bay among them *Avicena marina* species have high Above-ground biomass, ground carbon stock, and CO_2 absorption values of 1529.206 ton/ha, 261.318 ton/ha,2635 ton/ha.

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TALL BUILDING

ICSBE 2023-36

REVIEW OF FIRE RESCUE RESOURCES AND PUBLIC AWARENESS ON THE FIRE SAFETY OF HIGH-RISE BUILDINGS IN SRI LANKA

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Abstract: Maintaining fire safety in high-rise buildings is paramount, considering the challenges of evacuating occupants and controlling fires. Globally, fire hazards result in almost 1% of annual GDP losses. Moreover, past research has emphasized that building occupants should have a proper idea of how to evacuate, and the fire brigade should have enough resources and better operational practices to control a fire, particularly in high-rise buildings. Consequently, most countries prioritize the fire safety of high-rise buildings. With the recent changes to Sri Lanka's skyline with the number of high rises from 7 to 130 from 2006 to 2020, it is crucial to examine the fire safety protocols of high-rise buildings in Sri Lanka compared to international standards such as the National Fire Protection Association (NFPA). A document review and questionnaire survey were conducted to evaluate the adequacy of fire rescue resources and public awareness of high-rise building fires. An exponential growth of the high-rise building population in the Colombo Municipal Council (CMC) is identified. The study reveals that, although the number of fire stations for the CMC area is adequate with the international standards, the available resources in the Colombo fire service department are only adequate to extinguish a single high-rise building fire in one instance, not adequate for two or more simultaneous fires. Further, it was found that although people have an acceptable level of awareness of conventional active fire safety practices, 25% - 40% of the sample were unaware of the standard fire practices such as fire drills, refuge floors, voice evacuation, and fire-rated doors. The requirement of uplifting the fire and rescue resources required in high-rise building perspective currently available in the fire service department hence emerges. The identified lagging aspects of public awareness of fire safety measures also needed to be upgraded.

Keywords: Fire safety; Highrise buildings; Fire safety regulations; Fire rescue resources; Public awareness

1. Introduction

The land scarcity due to urban development has enhanced the spreading of tall buildings in Sri Lanka (Gunarathna *et al.*, 2014). A High-Rise building is defined by the National Fire Protection Association (NFPA, 2018) as a building with a height higher than 75 ft (23 m), measured above the lowest level of fire department vehicle access. In the Sri Lankan context, a high-rise building has been introduced as any building with more than ten floors including the ground floor, or whose height at any part of it above the ground level exceeds 30 meters (ICTAD, 2006). High-rise buildings comprise a high- potential for fire risk due to different levels of mobility, high concentration of occupants, difficulties in evacuating, excessive amounts of fuel load, limitation of fire department access, the existence of natural forces improving fire & smoke circulation, and complex design configuration (Craighead, 2009; Gunarathna *et al.*, 2014). The effects of high-rise fires comprise serious injuries to occupants, damage and property loss, and severe disturbances to normal building activities (Gunarathna *et al.*, 2014). Sri Lanka has reported 2703 fires between the year 1974 – 2007. (Rathnayake *et al.*, 2020). According to NFPA (Ahrens, 2016) between 2009 and 2013, the US fire department recorded an average of 14,500 structural fires per year in high-rise buildings which caused an annual average of 520 civilian fire injuries, 40 occupant fire deaths and $154 million in direct property loss. To assure high-rise buildings against fire damage, active and passive fire defense systems as shown in Figure 1 and fire safety rules & regulations have been established locally and internationally.

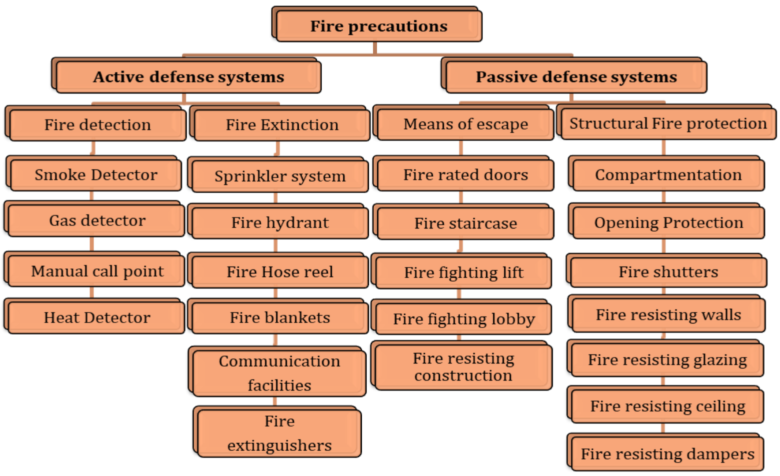

Figure 1: Different active and passive fire protection systems which practicing at buildings, reproduced using (Craighead, 2009; Fu, 2021; Furness and Muckett, 2007; Kironji, 2015; Rowan, 2014).

Active systems constrain fire development and its consequences in a fire incident by some actions taken by an automatic device or a person (Buchanan and Abu, 2001). Passive systems dominate the fire or its consequences by scenarios that are attached to the structure or material of the building which does not require any specific action in the event of a fire (Buchanan and Abu, 2001). CIDA Fire regulations (CIDA, 2018) is the actively referring local fire safety standard in Sri Lanka. Figure 2**Error! Reference source not found.** shows a summary of regulations provided in the CIDA fire regulations. Several international references such as International Building Code (IBC) (ICC, 2015), National Fire Protection Association (NFPA, 2020), International Fire Code (IFC) (ICC, 2012), British Standards (BS) (BSI, 2004), International Fire Safety Standards (IFSS) (IFSSC, 2020) and ISO (ISO, 2022) are followed when designing buildings against fire safety (Fu, 2021; Liyanapeli, 2017; Stollard *et al.*, 2014; Yung, 2008)

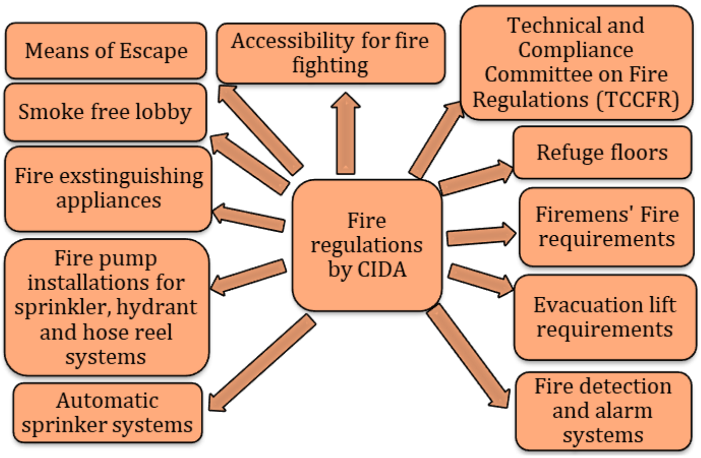

Figure 2: Different fire protection regulations provided by CIDA (CIDA, 2018).

Although many countries have developed high-rise buildings rapidly along with fire safety techniques, the parallel development of fire safety measures is lacking in the Sri Lankan construction industry (Aluthwala *et al.*, 2007). Since Sri Lanka has not yet experienced a severe fire in a high-rise building (Seneviratne, 2017), the attention on fire safety has fallen low (Aluthwala *et al.*, 2007). Another past study (Liyanapeli, 2017) revealed that the fire safety regulations currently used in the country lack enforceability. Furthermore, it is noted that many alterations happen in buildings after approving the original building plan (Liyanapeli, 2017). Building owners always tend to achieve only minimum fire safety measures per the standards (Li *et al.*, 2007). On the other extreme, some buildings are overprotected by fire safety requirements but are not cost-effective (Rathnayake *et al.*, 2020). Architects complain that incorporating modern building concepts is hard due to obstructive building fire and other codes (Li *et al.*, 2007). Hence, safety against fire in high-rise buildings is a prominent issue to be studied in the Sri Lankan built environment. The research is hence developed to address the identified gap by setting the aim as investigating the adequacy of fire safety resources and occupant awareness along with the rapid development of the high-rise building population in Sri Lanka compared to international standards. To address the aim, two research objectives have been formulated. The first objective is to study the evolution of the high-rise building population in Sri Lanka along with the fire history in Sri Lankan buildings and the adequacy of fire rescue facilities currently available in Sri Lanka. The second objective is to investigate the awareness level of people about the prevailing fire safety practices in buildings.

2. Research design

An overview of the overall research methodology is given in Figure 2 below.

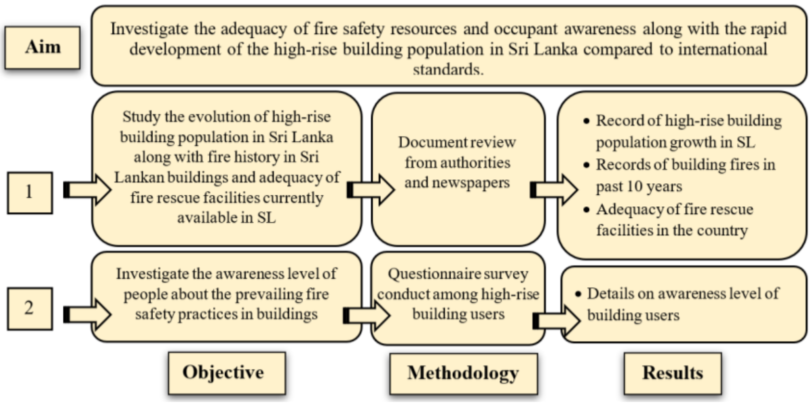

Figure 2: Overall methodology of the study.

In this study, firstly the high-rise building growth over 15 years was studied using data gathered from CMC (Colombo Municipal Council) and UDA (Urban Development Authority) records. Using the results of the study, the future high-rise building growth trend is predicted. Further, the past fire history within the CMC area was analyzed using the data collected from the Fire service department. The average number of fires per year was obtained. Then following the identified high-rise building growth rate, the prevailing higher probability of future building fires was forecasted. Considering both the facts obtained, the available fire rescue facilities in the Fire service department were studied and their adequacy against fire incidents in high-rise buildings was evaluated. It will give valuable insights into the enhancement of the fire rescue facilities in Sri Lanka. Finally, the high-rise building users' awareness of the high-rise building fires was assessed using s public questionnaire. Overall prominent outcomes of the questionnaire survey can be considered as important facts on the user awareness development.

3. Results and Discussions

3.1. Growth of High-rise buildings in the Colombo Municipal Council (CMC) area

Since most high-rise buildings were in the Colombo area, the Colombo Municipal Council (CMC) area was selected as the field of study. Details of buildings comprising more than 10 floors which were approved within the 2006-2020 period were collected from CMC and Urban Development Authority (UDA). Collected data were analyzed using the SPSS 22.0.0.0 Statistical software package (IBM Corporation, 2013). Auerbach and Wan, (2018) have determined that the number of skyscrapers completed in the 2050 year worldwide can be predicted using the follow on-linear model shown by Equation (1).

$$N_t = e^{(\alpha+\beta t)} \tag{1}$$

Where N_t is the number of skyscrapers completed in year t, t is the year, and α and β are constants. Assuming the same distribution and assuming all other parameters remain the same for the study period, the high-rise building population growth in the CMC area was modeled using a non-linear regression function in SPSS. The resulting graphs are shown in figure 4.

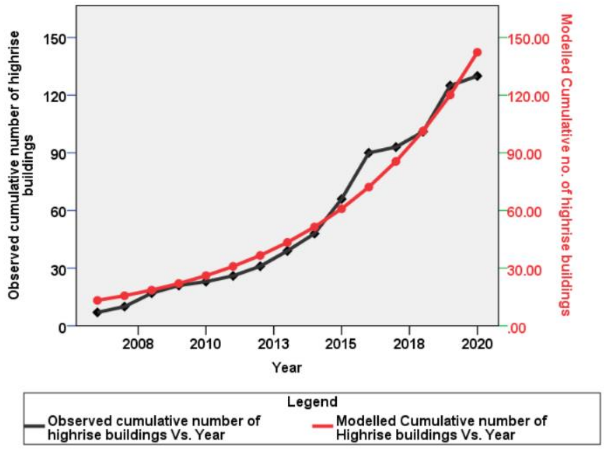

Figure 4: Resulted graphs of observed and modelled cumulative number of high-rise buildings in CMC area.

3.2. Past fire history in the CMC area

Data related to past fire incidents in the CMC area which were collected from the Colombo Fire Service Department were analyzed and plotted as shown in Figure 5.

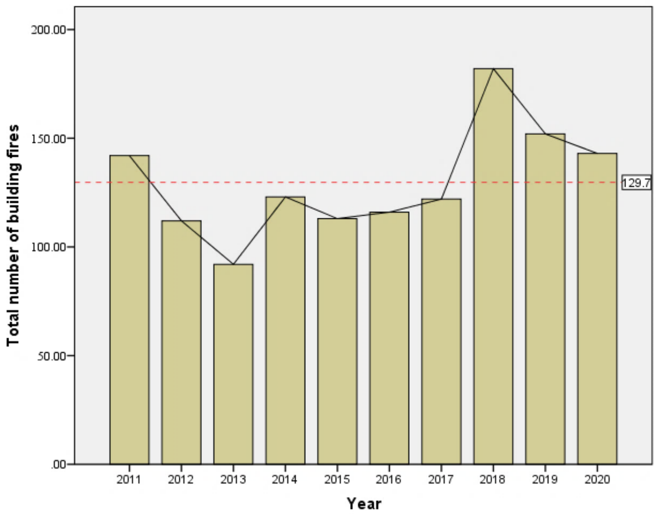

Figure 5: Bar chart showing total number of building fires vs. year with the average.

The bar chart given in Figure 5 resulted in an average number of 130 building fires per year as per the past 10 years' data. Since the high-rise building population is growing exponentially, more than 130 building fires could be expected in the upcoming year.

3.3. Adequacy of fire rescue resources

The prevailing fire rescue facilities in the Colombo fire service department were compared with international standards as in Table 1. Colombo Fire Service Department currently has several types of emergency vehicles for their fire and rescue services in 5 number of fire stations. Although the number of fire stations for the CMC area is adequate with the standards, the available resources both staff and appliances, are sufficient for a single fire to occur at an instance, but not sufficient for extinguishing two or more simultaneous high-rise building fires within the CMC area. The required standard minimum number of resources to extinguish two simultaneous high-rise building fires is tabulated in Table 1. Referred standards are older than 2010. Hence, it can be assumed that the required minimum number of resources for the current year is more than stated in Table 1. Due to the exponential growth pattern of the high-rises, consequently, the number of fires occurring simultaneously in the CMC area could be increased by 2030. It can be concluded that in the future minimum number of required resources shall be increased at least by 1.5 times the current requirement. Those outcomes are shown in Table 2.

Table 1: Comparison of available fire department resources with international standards.

Fire rescue resource	The prevailing amount in the Colombo Fire Service department	Recommended minimum value in international reference/standards	Citation for the reference	Adequacy of available resources
Fire stations	5	1 station per every 4.5 square miles of land. Required minimum as per standard = 4	Insurance Services Office (ISO(ii)) guidelines. (Portland Fire and Rescue, 2006)	Adequate
Firefighters	75	43 nos. for initial alarm deployment in high-hazard fire incidents.	NFPA 1710 (NFPA, 2016)	Adequate for a single fire at once.
Officers	8	3 per structural fire	NFPA Fire Protection Handbook (NFPA, 2003)	Adequate for two number of fires at once
Fire engines	7	4 per structural fire	NFPA Fire Protection Handbook (NFPA, 2003)	Adequate for a single fire at once.
Ladder trucks	2	2 per structural fire	NFPA Fire Protection Handbook (NFPA, 2003)	Adequate for a single fire at once.
Fire pumpers	7	4 per structural fire	NFPA Fire Protection Handbook (NFPA, 2003)	Adequate for a single fire at once.
Other aerial apparatus	1	0.01 per 1000 population	US fire department profile by NFPA (Fahy *et al.*, 2021)	0.002 per 1000 population is available. Not adequate
Other suppression vehicles	14	0.02 per 1000 population	US fire department profile by NFPA (Fahy *et al.*, 2021)	0.02 per 1000 population is available. Adequate

Table 2: Required minimum number of fire rescue resources for extinguishing two simultaneous high-rise building fire incidents and future needs.

Fire rescue resource	Currently available amount (2021)	The required amount to extinguish two coinciding high-rise building fires (2021)	The required amount to be extinguished more than two coinciding high-rise building fires (2030)
Fire engine	7	8	12
Turn table ladder	2	4	6
Fire pumper	7	8	12
Other areal apparatus	1	7	11
Other suppression apparatus	14	14	21
Fire officers	8	6	9
Firefighters	75	86	129

3.4. High-rise building user awareness on building fire safety

An online questionnaire survey was conducted to collect data about building user awareness of building fire safety. A questionnaire survey has been prepared as random sampling with mixed methods, quantitative and qualitative. The questions in the questionnaire survey were based on data gathered from the literature. Likert scale was used to obtain users' preferences on several aspects related to building fire safety. Visual/verbal/practical knowledge of fire safety measures in a high-rise building and the satisfaction level on prevailing fire safety awareness among the public were collected through the questionnaire survey conducted in 2022. Two hundred fifty (250) survey forms were distributed, and 97 responses were received.

Since most of the responses to the questionnaire were from highly populated districts of Galle (31%), Colombo (13%), and Gampaha (11%) and responses have been received from 20 districts in the country, the validity of the sample is acceptable, and a good distribution of sample can be seen. According to Figure , 69% of the sample has visited high-rise buildings in Sri Lanka. It indicated that the usage level of high-rise buildings has increased. 39% of the sample visited for official purposes while 28% visited for recreational purposes. As shown in Figure 6, 16% of the sample daily uses high-rise buildings for their work. Subsequently, there should be a set of updated fire safety practices with periodical maintenance should be conducted to assure the life safety of daily users of the high-rise buildings.

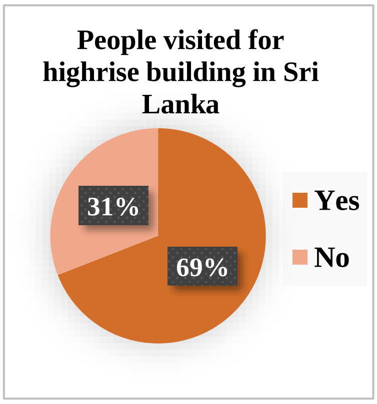

Figure 6: Percentage of people who visited high-rise buildings in SL.

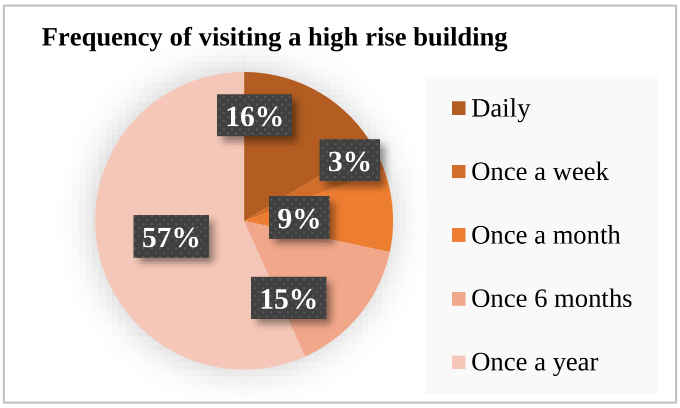

Figure 7: Frequency of visiting high-rise buildings.

According to Figure 7 25% - 40% of the sample have never heard about fire drills, refuge floors, voice evacuation, and fire-rated doors. Less than 10% of the sample only know well what a fire drill, refuge floor, and voice evacuation is. It hinders the weakness of the awareness of people about fire safety measures in buildings. 10%-35% of the sample always think that calling the fire department will lessen the damage by extinguishing. Therefore, to make such a desire applicable, the fire brigade should be strengthened appropriately. Although ordinary building users lack the technical knowledge verbally and visually, nearly 50% of the sample is correctly behaving in a case of fire. It is an outstanding trend. Only 13% of the sample has participated in a fire drill in their lifetime, as shown in Figure 3. It can be a strong drawback identified through this study. According to CIDA (CIDA, 2018), fire drills should be conducted every six months both in the construction and service stages. Only 2% of the sample is purely satisfied with the prevailing awareness about fire safety practices in Sri Lankan high-rise buildings as shown in Figure 8. Nearly 50% of the sample are unsatisfied with the public awareness of high-rise building fire safety.

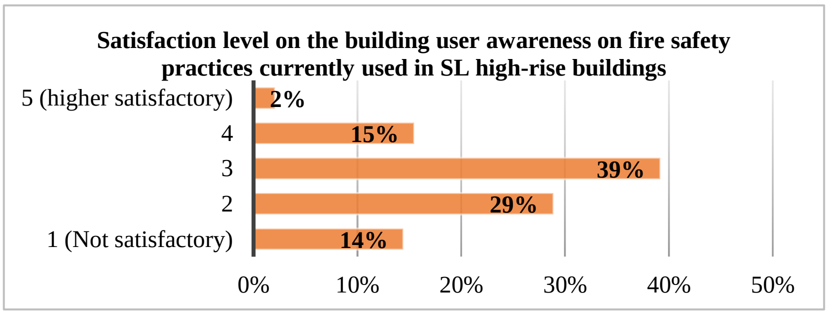

Figure 8: Satisfaction level of the building users on fire safety awareness level.

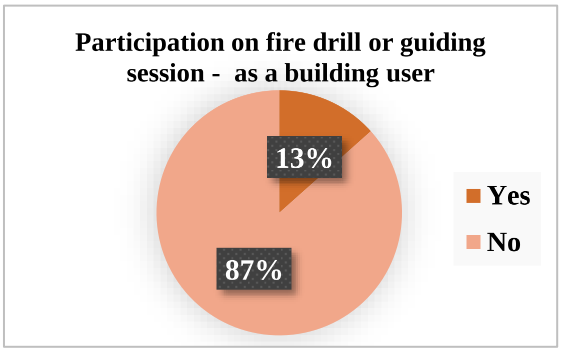

Figure 3: Participation on fire drill or guiding session.

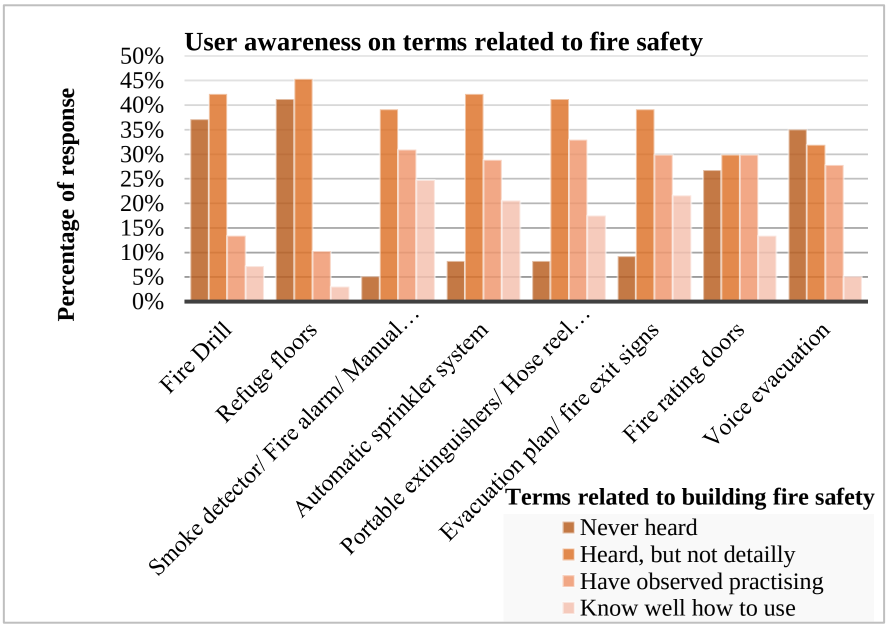

Figure 4: User awareness on terms related to fire safety.

4. Conclusions

Building fire hazards contribute to a considerable amount of economic and social damage worldwide. The study has investigated the fire safety of Sri Lankan high-rise buildings in two diverse ways, adequacy of fire rescue resources and user awareness of fire safety. The following can be identified as the key findings of the study. The high-rise building population in the CMC area has increased exponentially throughout 15 15-year period. 130 average number of fires have occurred in buildings in the past 10 years. The number of probable fires to occur in high-rise buildings will be increased than the current value, following the exponential growth of high-rise building populations. The available human and emergency vehicle resources are adequate only for a single fire that occurred at instance not adequate for two simultaneous high-rise fires in the CMC area. Public knowledge of fire drills, refuge floors, and voice evacuation methods is less. Although building users have less knowledge of fire safety practices verbally and visually, they have acceptable awareness of practical incidents of fire. Fire drills are less practiced among building users.

Table 3 shows suggested recommendations obtained through the analysis of the identified issues in the overall study. Those recommendations can be aided by the authorities and the stakeholders related to building fire safety.

Table 3: Recommendations from the study along with identified issues.

Identified issue	Recommendations from the study
Fire safety knowledge among a limited crowd is identified	Conduct building fire safety awareness programs that address high-rise building fire safety measures in schools, through higher education institutes, village-wise, and workplace-wise. Include general fire defense knowledge on the school syllabus for students.
The willingness to give dedicated attention to fire safety measures was less and the traditional instructing methods were less attractive.	Aware people through visual aids like using new technology (mobile applications, displaying videos on public screens, and the entrance of a high-rise building) about fire prevention methods.

Less dedicated fire safety-related staff were identified in studied high-rise buildings.	Appoint at least one executive person except for the fire warden system who is responsible for the high-rise building fire safety.
The Participation and knowledge of fire drills were less	Conduct more often fire drills in high-rises (once 6 months or soon).
Language differences matter for the awareness methods	Include fire safety instructions in 3 languages. (Sinhala, Tamil, English)
The shortage of fire and rescue resources required in the Fire Service Department in the CMC area	Improve fire and rescue resources currently available in Sri Lankan fire stations as compatible with the given amounts in the study as required for high-rise building fires.

The high-rise building population growth can be forecasted accurately considering other influencing parameters as dedicated future research work. The awareness of high-rise building users unfamiliar with online platforms hasn't been involved in the study, which is a limitation of the study. The fire service department could improve fire rescue facilities by taking the study as a preliminary guide.

Acknowledgments
This research was supported by the Science and Technology Human Resource Development Project, Ministry of Higher Education, Sri Lanka, funded by the Asian Development Bank (Grant No. R2/SJ1). Further, the study has been conducted with the aid of officials at the University of Sri Jayewardhenepura, Colombo Municipal Council (CMC), Urban Development Authority (UDA), Colombo Fire Service Department, and Maga Engineering (Pvt) Ltd.

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EVALUATION OF EARTHQUAKE DESIGN RESPONSE SPECTRA FOR SRI LANKA CONSIDERING SHORT-PERIOD EFFECTS

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Abstract: Sri Lanka lacks a comprehensive earthquake design guideline for seismic analysis and design of structures. Hence, engineers are forced to use foreign earthquake design codes for structural designing under seismic loads. This study focuses on the development of response spectra for Sri Lanka, considering the effects of short-period ground motions. Initially, the available earthquake design response spectra proposed in the literature were evaluated. Two categories of ground motions were selected: short periods with magnitudes less than 5.5 for soil type A, and short periods with magnitudes greater than 5.5 for soil type A. Soil classification was done based on the Eurocode 8 guidelines, and these ground motions were chosen from the PEER database. For short-period ground motions with magnitudes less than 5.5 for soil type A, it was observed that the mean plus standard deviation closely followed the response spectrum specified in Eurocode 8 for magnitudes less than 5.5 and soil type A. Moreover, the mean response spectrum was found to be well below the standard response spectra. For short-period ground motions with magnitudes greater than 5.5, the mean spectrum closely followed the response spectrum proposed by Venkatesian et al. (2017), while the mean plus standard deviation closely matched the response spectrum presented by Seneviaratne et al. (2020). Furthermore, to develop response spectra for other soil classes, the modification factors proposed in Eurocode 8 are recommended.

Keywords: Seismic; Ground Motions; Short period; Response spectrum

1. Introduction

Sri Lanka does not have proper guidelines for earthquake-resistant design of structures; their engineers are forced to adopt site-specific provisions from codes by foreign countries. This could lead to a knowledge gap and results could change. Sri Lanka is in the middle of the Indo-Australia tectonic plate which leads to less possibility of reaching earthquakes due to tectonic plate fractural movements. However, due to the geological formation, there is a significant possibility of occurring short-period as well as long-period earthquakes around Sri Lanka. Therefore, it is required to analyze the effect of short-period ground motions on Sri Lanka. This study considers sets of ground motions that have short-period effects, and then analyzing and comparing was done to have a correct understanding of the suitable response spectrum for Sri Lanka seismology for different earthquake possible conditions. Due to the seismological location of Sri Lanka, it is required to use far fault, non-pulse-like short-period ground motions. Selected ground motions were soil Type A (Rock or other rock-like geological formation, including at most 5 meters of weaker material at the surface- Shear velocity > 800m/s) as per the Eurocode 8 soil classification. Based on the selected ground motion analysis, the comparison was done as described in the methodology, and based on the results conclusions were made.

2. Literature Review

According to the available literature, the oldest known written account of an earthquake that struck Sri Lanka is found in a book that was published in Lisbon in 1616 and describes an incident that happened on April 14, 1615, not far from Colombo. There haven't been any other earthquakes of that size since. However, there were other earthquakes, including the ones in 1938 and 1940, which were felt throughout much of the island but did not result in any fatalities or material or serious damage. Very minor seismic activity (between 3 and 3.5 Richter scale) was observed in Sri Lanka in 1986.

In the study of Seneviaratne et al. (2020), a seismic hazard map for Sri Lanka has been proposed considering the average PGA value at different locations in the country. Considering the range of average values obtained, two seismic zones were proposed. Based on the seismic zones in the hazard map design response spectrum has been proposed that is suitable for all the seismic zones. The proposed response spectrum was designed considering the rock-type soil conditions.

$$SA = \begin{cases} (1+10T)*PGA & 0 \le T \le 0.15 \\ 2.5PGA & 0.15 \le T \le 0.5 \\ 1.25/T*PGA & 0.5 \le T \le 4.0 \end{cases}$$

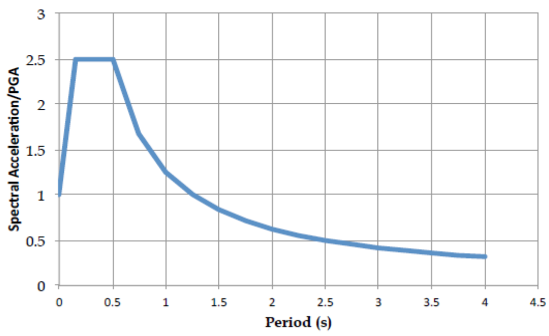

Figure 1: Proposed normalized response spectrum in Seneviratne at el. (2020).

The response spectra described in the EN 1998-1 Euro code 8: Design of structures for earthquake resistance, consist of mainly two types of design response spectra based on the magnitude of earthquake ground motions. Those are response spectrum - type 1, magnitude greater than 5.5 ground motions, and type 2 magnitude lesser than 5.5 ground motions. Each of these response spectra has developed considering all the soil types described as per the Euro code 8 guidelines. Respective amplification factors for each type of response spectra are shown below.

$$0 \le T \le T_B : S_e(T) = a_g \cdot S \cdot \left[1 + \frac{T}{T_B} \cdot (\eta \cdot 2{,}5 - 1)\right]$$

$$T_B \le T \le T_C : S_e(T) = a_g \cdot S \cdot \eta \cdot 2{,}5$$

$$T_C \le T \le T_D : S_e(T) = a_g \cdot S \cdot \eta \cdot 2{,}5\left[\frac{T_C}{T}\right]$$

$$T_D \le T \le 4\text{s} : S_e(T) = a_g \cdot S \cdot \eta \cdot 2{,}5\left[\frac{T_C T_D}{T^2}\right]$$

S_c(T) - The elastic response spectrum
T - Vibration period of a linear single-degree-of-freedom system
a_g - Design ground acceleration on type A ground
T_b - The lower limit of the period of the constant spectral acceleration branch
T_c - Upper limit of the period of the constant spectral acceleration branch
T_o - Value defining the beginning of the constant displacement response range of the spectrum
S - Soil factor
η- Damping correction factor with a reference value of η = 1 for 5%viscous damping

Table 1: Values of the parameters describing the recommended Type 1

Ground type	S	T_B (s)	T_C (s)	T_D (s)
A	1,0	0,15	0,4	2,0
B	1,2	0,15	0,5	2,0
C	1,15	0,20	0,6	2,0
D	1,35	0,20	0,8	2,0
E	1,4	0,15	0,5	2,0

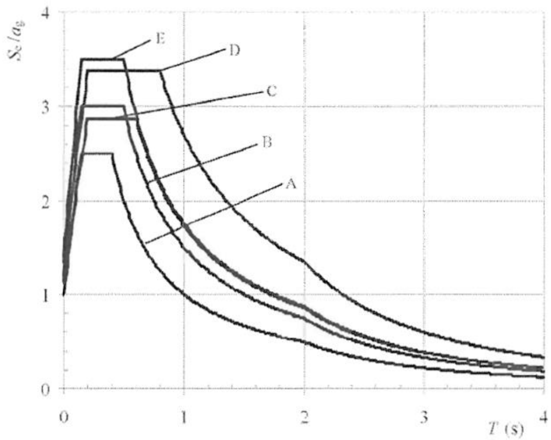

Figure 2: elastic response spectra and respective type 1 response spectrum.

In the study of Venkatesan et al. (2020) design acceleration response spectra on rock and soil for Sri Lanka are presented in this paper. Synthetic accelerograms using GENQKE (Lam, 1999) were developed for target Peak Ground Accelerations (PGA) of 0.08 g and 0.05 g based on the seismic hazard analyses for the region. Site response factors using SHAKE 91 (Idriss, 1991) were derived from five borehole records for sites consistent with the definitions of notional site class C and D based on shear wave velocity averaged over the whole depth and natural period. Maximum response spectral displacement observed on soil sites and the acceleration observed on rock sites in Sri Lanka were found to be representative of low-moderate seismic behavior. Based on these observations, design response spectra are presented in useful formats for the benefit of practicing engineers, and simple manual calculations for the construction of site-specific spectra are presented.

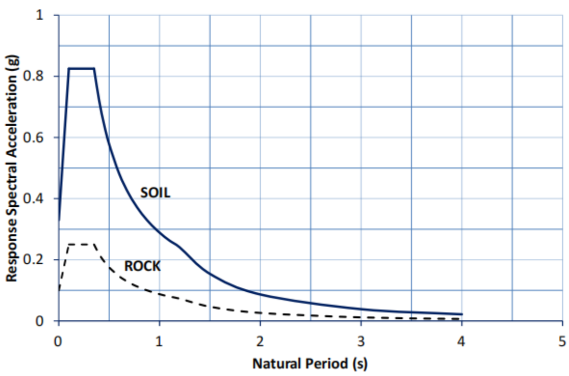

Figure 3: Recommended design response spectra on rock and soil.

$$0 \le T \le TB : Se\ (T) = ag.S.[1+ (T/TB)*(2.5-1)]$$

$$TB \le T \le TC : Se\ (T) = ag.S.2.5$$

$$TC \le T \le TD : Se\ (T) = ag.S.2.5\ [\ TC / T\ ]$$

$$TD \le T \le 4s : Se\ (T) = ag.S.2.5\ [\ TC\ TD/T2\ ]$$

Se(T) is the elastic response spectrum;
T is the vibration period of a linear single-degree-of-freedom system;
ag is the design ground acceleration on the type of ground
TB is the lower limit of the period of the constant spectral acceleration branch;
TC is the upper limit of the period of the constant spectral acceleration branch;

TD is the value defining the beginning of the constant displacement response range of the spectrum;
S is the soil factor;
(5% viscous damping assumed in the above equations)

Response spectra are described in the Australian Code mainly for 5 subsoil categories, which are strong rock, rock, shallow soil, deep or soft soil, and very soft soil. The respective amplification factors for each type of soil category are shown below.

Table 2: AS1170.4 Normalized Response Spectra for Different sub soil classes

Soil Category	$\mathbf{0 < T \leq 0.1}$	$\mathbf{0.1 < T \leq 1.5}$	$\mathbf{T > 1.5}$
Strong Rock	0.8 + 15.5 T	0.704/T but ≤ 2.94	$1.056/T^2$
Rock	1.0 + 19.4T	0.88/T but ≤ 2.94	$1.32/T^2$
Shallow Soil	1.3 + 23.8T	1.25/T but ≤ 3.68	$1.874/T^2$
Deep or soft soil	1.1 + 25.8T	1.98/T but less-but≤ 3.68	$2.97/T^2$
Very soft soil	1.1 + 25.8T	3.08/T but≤ 3.68	$4.62/T^2$

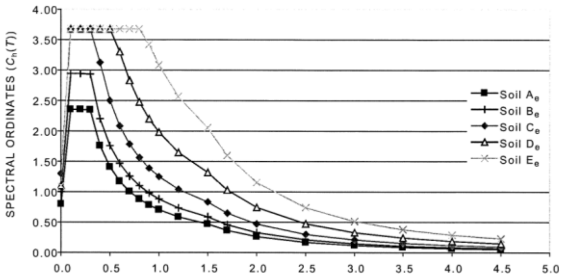

Figure 4: AS1170.4 Normalized Response Spectra for different subsoil classes.

3. Methodology

To achieve this objective, we extracted suitable types of ground motions that could occur in a country like Sri Lanka which has the properties of far fault, non-pulse like short and long period ground motions from the PEER (Pacific Earthquake Engineering Research Center) database. The extracted ground motions were then categorized into two sections, based on the magnitude, soil condition of the recorded station, and mean period of the ground motion. The first section included short-period ground motions with a magnitude greater than 5.5 and the second section included short-period ground motions with a magnitude lesser than 5.5. All the ground motions that were selected in these two categories include only the soil type of rock. To separate ground motion based on soil condition Eurocode 8 specified ground motion separation criteria based on shear velocity used. Ground motions that have a mean period lesser than 1.0 are considered short-period ground motions.

After categorization, we developed mean and mean plus standard deviation response spectra for each category of ground motion. The response spectra provide a graphical representation of the maximum response of a structure to different ground motion intensities for a given period. The mean response spectra give the expected value of the response of a structure, while the mean plus standard deviation response spectra give an idea of the possible range of the response of a structure.

To have a detailed understanding of how response spectra behave in different earthquake types, we selected the best match ground motions for each category and plotted the respective response spectra. The best match ground motions were chosen based on the similarity in their seismic characteristics to those of Sri Lanka. The response spectra for each category showed different shapes and peak amplitudes, indicating the variation in seismic characteristics of different types of earthquakes.

Finally, in the analysis section, we compared the developed response spectra in each category with the standard design response spectra available in the world such as the Sri Lanka standard response spectra mentioned in Senavirathna et.al., (2020 paper, Venkatesan et.al.,(2017) paper, Eurocode specified, Indian Standard and Australian Standard response spectra. The developed response spectra for short-period ground motions were approximately within the range of the standard design response spectra.

4. Results

In this research far fault, non-pulse-like ground motions were further categorized based on the magnitude of the earthquake and the mean period of the ground motion. Mainly for magnitudes greater than or equal to 5.5 ground motions it was possible to collect long-period as well as short-period ground motions. For magnitudes less than 5.5 ground motions only short-period ground motions existed. In conclusion, we have separated collected ground motions into three categories magnitude greater than 5.5 long-period ground motions, magnitude greater than 5.5 short-period ground motions, and magnitude less than 5.5 short-period ground motions of soil type A, then compare respective response spectra with the already existing standard response spectra available in the world.

As the standard response spectra of Sri Lankan Senavirathna et.al.,(2020) paper, Venkatesan et.al.,(2017) paper, Indian Standard response spectrum for soil type – rock, Euro-code 8 response spectrum of magnitude greater than 5.5 for soil type - rock, Australian codes response spectrum for soil type rock were used. In addition to the standard response spectrum for each country mentioned previously two response spectra for records near to Himalayan and Andaman Islands were also mentioned in the comparison to take the idea of how the response spectra alike in the south Indian region with collected data from the PEER database.

4.1 Magnitude greater than 5.5, Short period ground motion analysis

In this section mean and mean plus standard deviation response spectra of 35 short period, far fault, and non-pulse-like ground motions with magnitude greater than 5.5 were analyzed. Out of 35 response spectra related to best match 7, 10, 20, and 30 ground motions were analyzed separately. Analysis results are shown in bellow figures below.

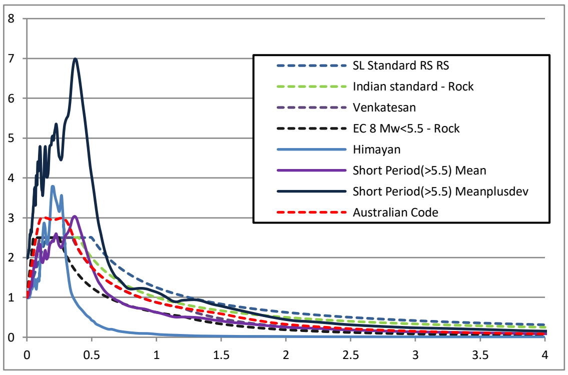

Figure 5: Response spectra comparison. Best match 10 out of 35 short-period ground motions magnitude greater than 5.5.

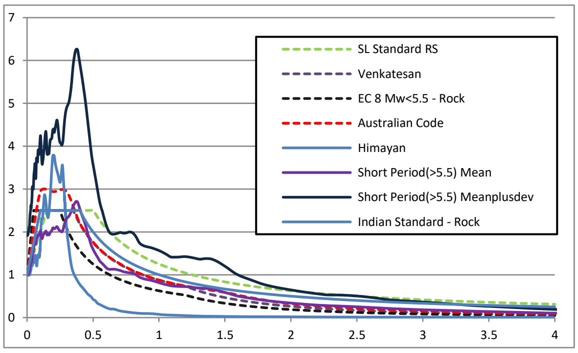

Figure 6: Response spectra comparison. Best match 20 out of 35 short-period ground motions magnitude greater than 5.5.

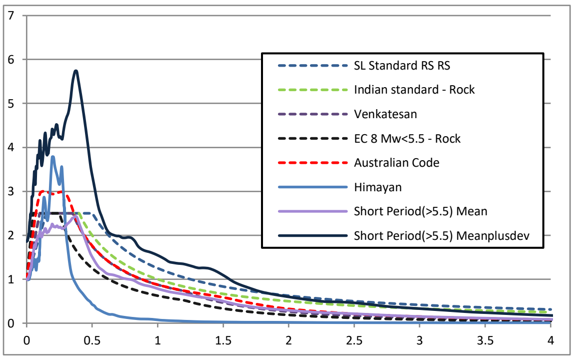

Figure 7: Response spectra comparison. Best match 30 out of 35 short-period ground motions magnitude greater than 5.5.

4.2 Magnitude lesser than 5.5, Short period ground motion analysis

In this section mean and mean plus standard deviation response spectra of 55 short period, far fault, and non-pulse-like ground motions with magnitude greater than 5.5 were analyzed. Out of 55 response spectra related to best match 7, 10, 20, 30, and 50 ground motions were analyzed separately. Analysis results are shown in the below figures.

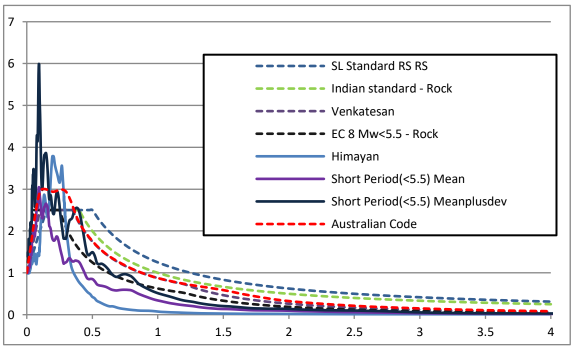

Figure 8: Response spectra comparison. Best match 7 out of 55 short period ground motions magnitude lesser than 5.5.

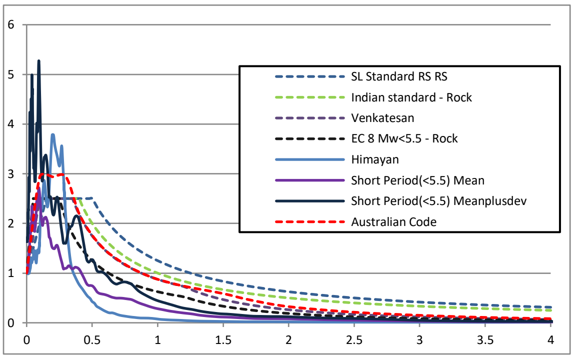

Figure 9: Response spectra comparison. Best match 10 out of 55 short-period ground motions magnitude lesser than 5.5.

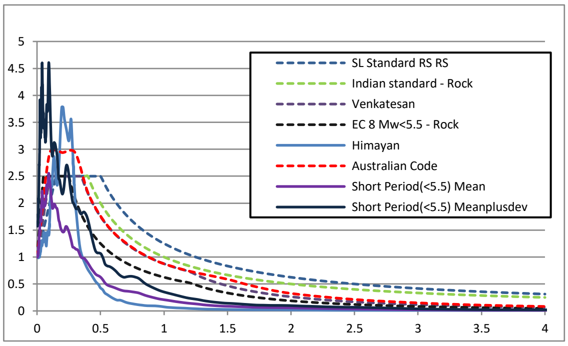

Figure 10: Response spectra comparison. Best match 20 out of 55 short-period ground motions magnitude lesser than 5.5.

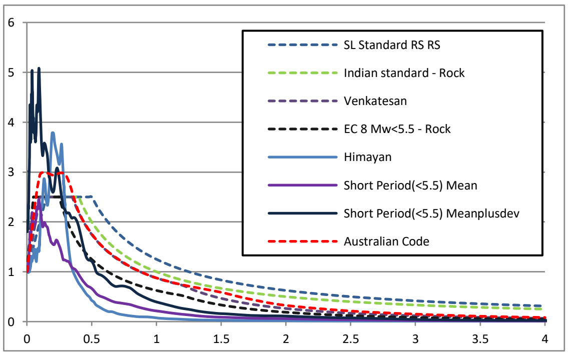

Figure 11: Response spectra comparison. Best match 30 out of 55 short-period ground motions magnitude lesser than 5.5.

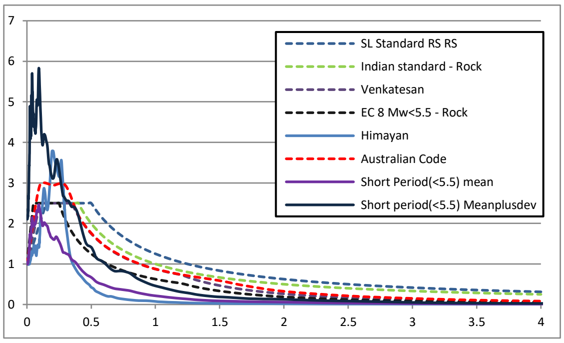

Figure 12: Response spectra comparison. Best match 50 out of 55 short-period ground motions magnitude lesser than 5.5.

5. Conclusions

The developed response spectrum for ground motion category magnitudes greater than 5.5, short-period ground motions it was found that the mean spectrum closely follows Venkatesian et al. 2017 while the mean plus standard deviation closely follows the Seneviaratne et al. 2020.

The developed response spectrum for ground motion category magnitudes lesser than 5.5 short-period ground motions, it was found that mean plus standard deviation closely followed the Eurocode 8 specified response spectrum for magnitude less than 5.5, soil type A and mean response spectrum was well below the standard response spectra.

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IDENTIFICATION OF NATURAL FREQUENCY AND DAMPING RATIO OF TALL BUILDINGS IN SRI LANKA USING AMBIENT WIND VIBRATION DATA

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Abstract: In recent years, the demand for tall buildings in Sri Lanka has rapidly increased. When evaluating the wind design aspects of tall buildings, it becomes evident that the natural frequency and damping ratio assume utmost importance. These two factors play a pivotal role in accurately estimating the design wind load and forecasting wind-induced responses for such structures. Nonetheless, within the Sri Lankan context, a conspicuous gap exists as there is an absence of empirical formulations tailored for the estimation of these dynamic parameters essential for wind engineering design. Consequently, there is a compelling need to establish a comprehensive database comprising identified natural frequencies and damping ratios specific to tall buildings in Sri Lanka. These findings will serve as the basis for proposing empirical equations to estimate the fundamental natural frequencies and damping ratios. In this study, the natural frequency and damping ratio of selected existing tall buildings in Sri Lanka, are estimated using ambient wind vibration data and operational modal analysis techniques. The random decrement technique (RDT) was used to obtain free vibration response from ambient vibration data. Then, Fast Fourier Transformation (FFT) and Continuous Wavelet Transformation (CWT) were used to estimate the natural frequency and damping ratio. CWT is widely used to identify the dynamic properties of tall buildings and can provide reliable results compared to other methods. When the results were compared to the values calculated using design codes, it was observed that the damping ratios tended to be higher than anticipated, while the natural frequencies were found to align quite well with the calculated values from the literature. Further identification of the natural frequency and damping ratio of existing tall buildings is recommended to develop a database of the dynamic properties of tall buildings in Sri Lanka.

Keywords: Continuous Wavelet Transformation; Damping ratio; Natural frequency; Tall buildings

1. Introduction

1.1 Background

In Sri Lanka, the rapid rise in tall buildings, particularly in urban areas, is met with the challenge of dominant dynamic loads, primarily wind forces. Ensuring the structural stability and safety of these buildings necessitates accurate estimation of dynamic responses like displacement, velocity, and acceleration. Natural frequency and damping ratio stand as pivotal factors in estimating the dynamic response and design wind load for tall buildings. However, in Sri Lanka, there is currently no established empirical formula for estimating the natural frequency and damping ratio. Consequently, engineers rely on experiential judgments, leading to potential issues during high winds, such as excessive sway and inadequate bracing. To address this gap, it is crucial to establish a region-specific empirical formula. To achieve this, a comprehensive database, containing natural frequency and damping ratio values of existing buildings, is indispensable. This database will serve as the cornerstone for formulating a reliable approach, vital for the effective design and safety of tall buildings in Sri Lanka.

The dynamic parameters of a structure, including natural frequency, damping ratio, and mode shapes, are essential for understanding its behavior. Modal analysis is a widely used technique for identifying these dynamic parameters. It utilizes acceleration or velocity data from vibration tests. These tests fall into three categories: free vibration tests (caused by initial excitation), forced vibration tests (under constant excitation), and ambient vibration tests (caused by external factors like wind, traffic, and human activities). There are two main modal analysis methods: Experimental Modal Analysis (EMA) employs artificial excitation, while Operational Modal Analysis (OMA) relies on ambient vibration data (Ghalishooyan and Shooshtari, 2015). In tall buildings, capturing responses from higher modes due to their substantial weight poses challenges. To address this, ambient wind vibration data, crucial for in-situ analysis (Birtharia and Jain, 2015), is utilized with Operational Modal Analysis (OMA) techniques. For precise identification, the data is converted into free vibrations using the random decrement technique (RDT). Subsequently, Continuous Wavelet Transform (CWT) is applied for accurate dynamic parameter identification. Additionally, dynamic parameters are determined using the Fast Fourier Transform (FFT). Finally, the identified natural frequencies and damping ratio values are compared with calculated values from equations available in the literature, as well as values obtained from Finite Element Models (FEM), ensuring a comprehensive validation process.

1.2 Objectives

The objectives of this study are as follows:

- Database Development: To construct a comprehensive database containing natural frequency and damping ratio data specific to tall buildings in Sri Lanka. This objective forms the foundation for the analysis of the dynamic behavior of these structures.
- Comparative Analysis: To compare the estimated natural frequency and damping ratio values obtained from the developed database with calculated values from relevant literature equations. This comparative analysis ensures the accuracy and reliability of the data used in the study.
- Numerical Validation: To validate the obtained results by comparing them with numerical data obtained from Finite Element Models (FEM). This validation step is crucial for confirming the accuracy of the findings and enhancing the credibility of the study’s outcomes.

1.3 Natural Frequency

The natural frequency of a tall building is influenced by factors such as its height, tip acceleration/displacement (Tamura, 2012), and building type. Typically, these values are derived using empirical equations. The summarized methods and findings are presented Table 1.

Table 1: Methods to calculate natural period/frequency available in the literature (Ha, Shin, & Kim, 2020, p.1568).

Code	Structural Type	Natural Period
ASCE 7-10	RC moment frame	$T = 0.0670H^{0.9}$
	Other RC building	T = 0.043H
Lagomarsino	RC	T = H/55
Eurocode 1	RC	T = H/46
AS/NZS 1170 and Hong Kong design code	Steel and RC	T = H/46
Yukio Tamura	RC	T = H/67 (Habitability regime) T=H/55 (Safety-regime)

1.4 Damping

Damping is pivotal in the dynamic design of tall buildings. It dissipates vibration energy, averting failures like yielding or fatigue. There are various physical causes of damping in buildings (AIJ 2000) such as internal friction damping, plasticity damping, external friction damping, radiation damping, external viscosity damping, aerodynamic damping, and others.

Damping design values for general buildings widely vary across countries, typically falling between 0.3% and 5% for steel buildings and 0.5% to 5% for Reinforced Concrete (RC) buildings. This significant dispersion in design damping values is documented by Tamura et al. (2000). Formulas for calculating the damping ratio can be classified into two categories: single-value damping ratio and frequency/amplitude-dependent damping ratio.

1) Single-value damping ratio: Formulas falling under this category provide specific damping values irrespective of the building's natural frequency or magnitude of response under wind loads. Table 2 shows the values for structural damping ratios given by different codes under the Single-value damping ratio category.

Table 2: Values of structural damping ratios given by different codes under Single-value damping ratio (Ha, Shin, & Kim, 2020, p.1568).

Code	Structural Type	Structural Damping Ratio(ζ_s)
Eurocode 1	RC	1.57%
	Steel	0.79%
	SRC	1.27%
AS/NZS 1170 ASCE	RC or Prestressed concrete	0.5-1.0% (SLS) 2.0% (ULS)
	Steel	0.5-1.0% (SLS) 5.0% (ULS)
	RC	2.0%

2) Frequency and Amplitude-Dependent Damping Ratio: In contrast to single-value damping ratio formulas, this category provides varying damping values based on the building's natural frequency and response magnitude under wind loads.

Table 3: Values of structural damping ratios given by different codes under Frequency and amplitude-dependent damping ratio (Ha, Shin, & Kim, 2020, p.1568).

Code	Structural Type	Damping Ratio
ISO 4354	RC	ζ_s=1.2-2.0% (height dependent)
	Steel	ζ_s=1.0-1.8% (height dependent)
AIJ 2000	RC	$\zeta=0.0014f_1 + 470(X/H) - 0.0018$
	Steel	$\zeta=0.0013f_1 + 400(X/H) - 0.0029$
ESDU 83009		$\zeta=0.0076f_1 + 150(X/H) + 0.003$
Yoon		$\zeta=0.0057f_1 + 310(X/H) + 0.0057$ (For shorter direction)
		$\zeta=0.0059f_1 + 310(X/H) + 0.0039$ (For longer direction)

2. Methodology

2.1 Work Breakdown

The research work was conducted in several main steps, outlined in the flowchart presented below, illustrating the sequence of activities carried out during the research period.

Select the input dynamic responses
Tip acceleration of tall building

⇩

Measure the wind speed
Obtain wind speed at the site

⇩

Measure the ambient vibration data
Collect Ambient Vibration Data by using Accelerometers

⇩

Filter frequency responses
Noise removing from the collected data

⇩

Obtain free vibration response
Use RDT method

⇩

Identify Natural Frequency, Damping ratio and mode shapes
Wavelet Transformation

⇩

Compare Results
Compare estimated values with proposed value in literature

2.2 Data Collection

Luna Tower and Twin Peak buildings were chosen as the case study for this project; both structures are situated in Colombo, with heights of 170m and 182m, respectively. The dynamic response of the buildings under ambient wind vibration was captured through acceleration measurements. To measure acceleration, two accelerometers were strategically placed on the top floor. Measurements were collected at rates of 200Hz and 500Hz over a duration of 30-40 minutes in two perpendicular translation directions, as illustrated in the following figures. Concurrently, the wind speed at the top of the building was recorded at the time vibration data was measured, providing crucial contextual information for the study.

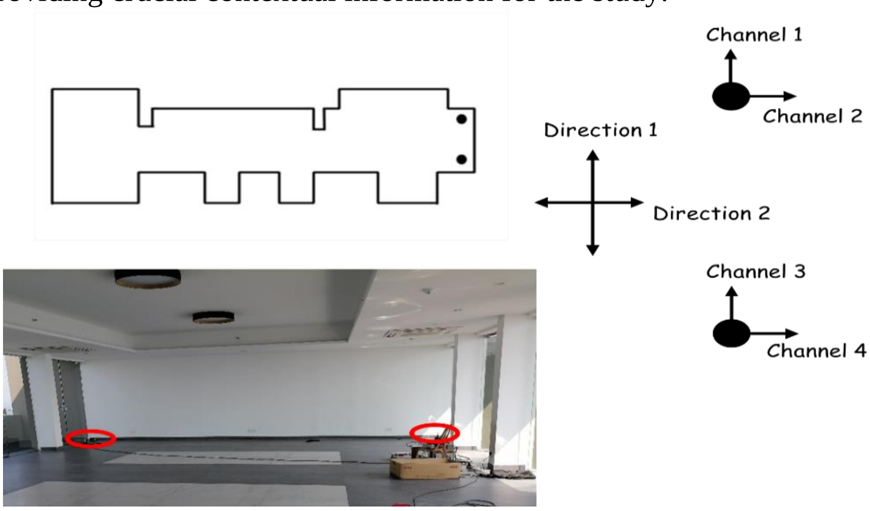

Figure 1: Arrangement of two accelerometers on the top floor of Luna Tower.

Figure 2: Arrangement of two accelerometers on the top floor of the Twin Peak building.

2.3 Data Processing

2.3.1 Noice removal method

Noise naturally infiltrates the dataset during the process of collecting acceleration data, constituting an unwanted and meaningless addition. The removal of this disruptive phenomenon is crucial in any meaningful signal analysis. Over the years, numerous researchers have devised various techniques for effectively eliminating noise while preserving the integrity of the original signal. In this study, the Butterworth filter is employed for noise removal. Specifically chosen for its ability to maintain maximum passband flatness, the Butterworth filter (Liyana Kankanamge, 2016) plays a pivotal role in ensuring the accuracy and reliability of our data analysis. Figure 3(b) demonstrates a filtered signal obtained from the raw signal using the Butterworth filter.

2.3.2 Random decrement technique

In this study, Continuous Wavelet Transform (CWT) is utilized to identify dynamic parameters of the building, such as natural frequency, damping ratio, and mode shapes, employing ambient vibration data. While wavelet estimation techniques are typically designed for analyzing free responses of systems, ambient vibration data inherently presents as random responses. To facilitate meaningful analysis, these random responses are transformed into free decay responses using the Random Decrement Technique (RDT). RDT is a well-established method employed to decompose the acceleration response into free and forced vibration components (M.R.

Hemtaei and S.A. Anvar, 2008). The free vibration component contains impulse/step responses, while the forced vibration component represents the building's response to random wind loads. Through a specialized averaging procedure, the free vibration component is isolated from the measurements. This process effectively removes the random elements, leaving only the deterministic part for precise analysis of the building's dynamic behavior. Figure 3(c) provides an illustrative example of the free vibration response obtained from ambient vibration data using RDT.

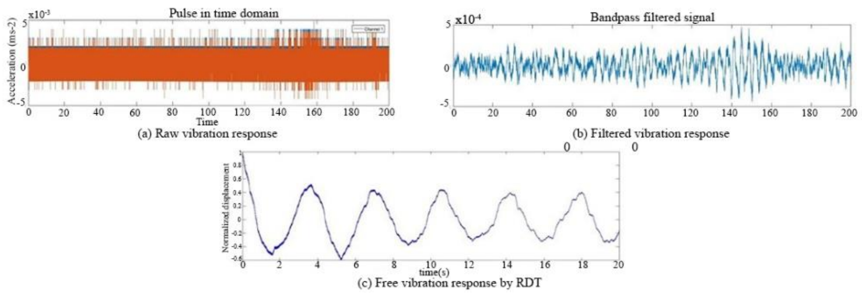

Figure3: Example of free vibration response obtained using RDT.

The Continuous Wavelet Transform (CWT) is utilized to analyze the building's free vibration response, enabling the identification of natural frequency, damping ratio, and mode shape.

2.4 Identification of Dynamic Properties

2.4.1 Natural Frequency

The natural frequency of the building was determined using both FFT and CWT methods.
The general CWT formula (Wu, 2001), used to decompose a function X(t) into the frequency-time domain, is represented by Equation (1).

$$CWT\{x(t)\} = W_x(\tau, s) = \frac{1}{\sqrt{s}} \int_{-\infty}^{+\infty} x(t)\psi^* \left(\frac{t-\tau}{s}\right) dt \tag{1}$$

In the equation, $\psi*$ represents the complex conjugate of ψ, t denotes time, $W\ (\tau,)$ measures the similitude between the function (t), the translation (τ) and the scale (s). The amplitude of the wavelet coefficient, $|W\ (\tau,)\ |$, constructs the wavelet amplitude map, displaying original signal features and their temporal variations. Local maxima in this map pinpoint system natural frequencies

2.4.2 Modal damping ratio

From the Wavelet amplitude map, the wavelet envelop $|W\ x\ (\tau,)\ |$ is extracted at natural frequencies. Wavelet envelops and the following equations are used to obtain the damping ratio.

$$T_i = \frac{2\pi}{\omega_{di}} \tag{2}$$

T_i is the natural period of the i^{th} mode of the structure.

$$\partial_i = \frac{1}{m} \ln \frac{|W_{xi}(t, \omega_{di})|}{|W_{xi}(t + mT_i, \omega_{di})|} \tag{3}$$

$$\zeta_i = \frac{\partial_i}{\sqrt{4\pi^2 + \partial_i^2}} \tag{4}$$

The equation (3) for Logarithmic decrement ∂_i, is used to calculate damping ratio ζ_i in the equation (4).

2.4.3 CWT-based damping ratio extraction procedure using MATLAB

A MATLAB program, specifically developed, is employed for estimating damping ratios from the measured free response of the vibration system. The program includes the following steps:

- Transforming the time signal into the time-frequency domain using CWT.
- Detecting wavelet ridges in the wavelet plot to estimate natural frequencies.
- Extracting the wavelet envelope at these natural frequencies.
- Plotting the wavelet envelope at the selected natural frequency on a natural algorithm scale.
- Estimating the damping ratio by determining the slope of the plot above.
- The least square method is applied to the linear plot of the natural algorithm to obtain the regression line.
- Regression line represents the following equation,

$$\ln\left|\left(w_g x\right)(a_0, b)\right| = -\delta w_n b + \ln\left(A_0 |G^*(\pm i a_0 w_n \sqrt{1-\delta^2}|\right) \tag{5}$$

- Finally, the damping ratio (δ) is estimated by taking the slope of the regression line.

3. Result and Discussion

3.1 Validation of the numerical algorithms

In this research, MATLAB-coded CWT and FFT numerical algorithms, discussed in the previous chapter, were utilized for estimation purposes. To validate their accuracy, a numerical signal with known frequencies and damping ratios was constructed. MATLAB codes were then employed to identify the frequencies and damping ratios of these signals, and the results were compared against the known values for verification.

A test signal with known frequencies and damping ratios was created (Table 4, Figure 4). Local maxima in both FFT and CWT analyses identified the frequencies, and CWT was employed for estimating damping ratios. The wavelet envelope, extracted from the wavelet amplitude map, aided in this process. Damping ratios were calculated by plotting the natural logarithm of these values, following the method explained in the previous chapter. Equation 6 represents the test signal used in this validation process.

$$X(t) = \sum_{i=1}^{3} \{e^{-\zeta\omega t}[((v_o + u_0\zeta\omega)/\omega_d)*\sin(\omega_d*t) + u_v*\cos(\omega_d*t)] \tag{6}$$

Table 4: Parameters of the Test signal

Parameters	i=1	i=2	i=3
Natural frequency (f) /(Hz)	0.2	0.5	1
Eigen frequency (ω) /(Hz)	1.256	3.142	6.283
Damping ratio (ζ)	0.01	0.05	0.02
Damped eigen frequency (ω_d)	1.256	3.138	6.282
Initial displacement (X0) /(m)	0.063	0.010	0.003
Initial speed (V0) /(ms^{-1})	0	0	0

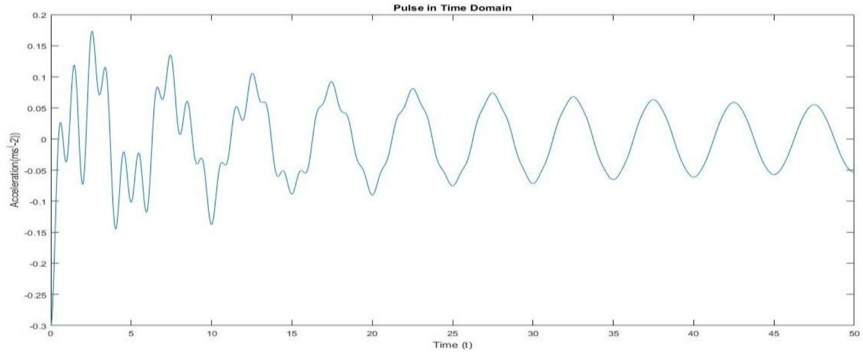

Figure 4: Test Signal.

Figure 5 illustrates the power frequency spectrum obtained through FFT and CWT analyses, respectively. Table 5 presents a comparative analysis between the calculated natural frequencies and their corresponding actual values.

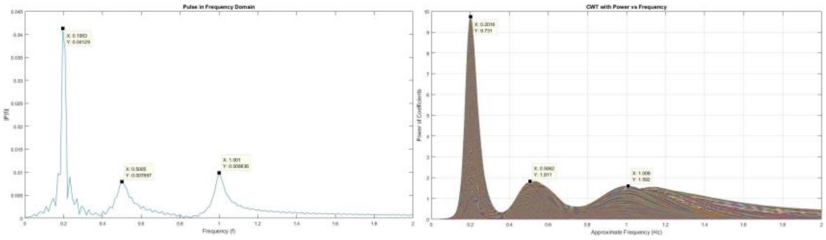

Figure 5: FFT and CWT power frequency spectrum.

Table 5: Comparison of Obtained Natural Frequencies with Actual Values

Test Signal Component	**Implemented Natural Frequency /(Hz)**	**Natural Frequency using FFT /(Hz)**	**Natural Frequency using CWT /(Hz)**
1	0.2	0.195	0.202
2	0.5	0.501	0.506
3	1	1.00	1.01

Figure 6 illustrates the wavelet amplitude map, followed by the wavelet envelope and its natural logarithm at a chosen natural frequency in the subsequent figure 7. Additionally, Table 6 compares the obtained damping ratios with the actual values.

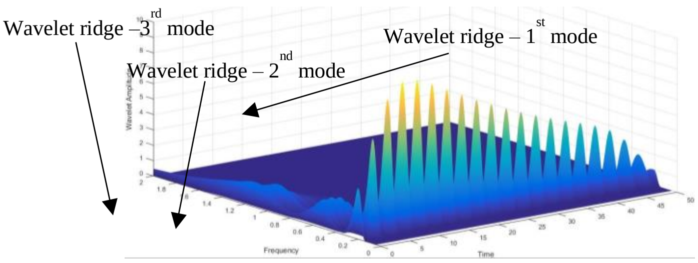

Figure 6: Wavelet amplitude map.

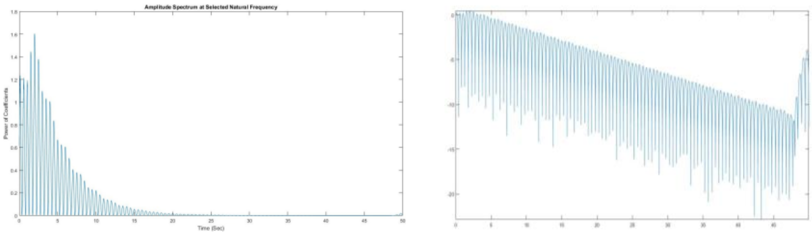

Figure 7: Wavelet envelope and natural logarithm of the wavelet envelope at 1.01 Hz.

Table 6: Comparison of Experimental Damping Ratios with Actual Values

Natural frequency	**Damping ratios**		**Error (%)**
	Implemented value	***Estimated value***	
0.2	0.01	0.0109	0.2
0.5	0.05	0.0501	0.5
1.0	0.02	0.0198	1.0

According to Tables 5 and 6, the results demonstrate a significant alignment with the implemented values. This consistency confirms the successful validation of the numerical algorithms utilized in the study.

3.2 Luna Tower and Twin Peaks Tower

3.2.1 Finite Element Analysis

In the design review report for Capitol Twin Peaks, modal analysis was performed using SAP 2000 with a 3D finite element model. Beams and columns were modeled with frame elements, while shear walls and floor slabs were represented by shell elements. The study extracted fundamental vibration modes and corresponding frequencies through modal analysis of separate finite element models, as illustrated in Figure 8.

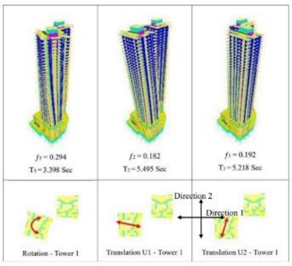

Figure 8: FFT and CWT power spectrum for channel 2.

The Ritz vectors method is used in the model analysis. The mass definition is 1DL+0.25LL.

Table 7: Model analysis results

State	**Mode 1 (Y) /(Hz)**	**Mode 2 (ZZ) /(Hz)**	**Mode 3 (X) /(Hz)**
SLS	0.16	0.18	0.24
ULS	0.15	0.17	0.23

3.2.2 Natural frequency

The natural frequency was determined in two perpendicular directions using data collected from accelerometers. Specifically, Channel 1 and 3 data were utilized for direction 1, while Channel 2 and 4 data were employed for direction 2.

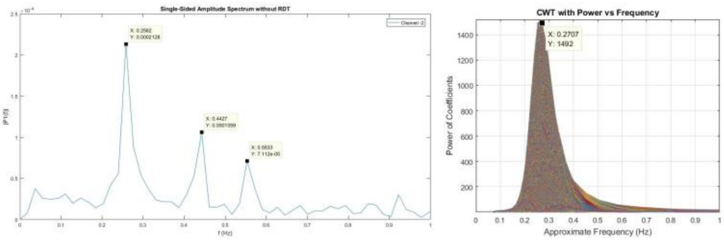

Figure 9: FFT and CWT power spectrum for channel 2.

Table 8 compares the natural frequency values obtained from the empirical equation with those derived through CWT, FFT, and FEM methods.

Table 8: Natural Frequency Comparison: FFT, CWT, FEM and Empirical Methods

Code	Natural Frequency (Hz)			
	Luna Tower		Twin Peaks Tower	
	Direction 1	***Direction 2***	***Direction 1***	***Direction 2***
KBC 2009	0.29	0.29	0.28	0.28
ASCE 7 - 10	0.15	0.15	0.14	0.14
Lagomarsino	0.32	0.32	0.30	0.30
Eurocode 1	0.27	0.27	0.25	0.25
Satake et al.	0.39	0.39	0.37	0.37
Yoon and Joo	0.31	0.31	0.29	0.29
Using FFT	0.26	0.26	0.30	0.29
Using CWT	0.25	0.27	0.31	0.30
Using FEM	0.16	0.24	0.18	0.19

3.2.3 Damping Ratio

The 3D wavelet amplitude map, along with the wavelet envelope at the selected natural frequency and their corresponding natural logarithmic plots for a specific channel, are presented in Figures 10. Additionally, Table 9 displays the estimated damping ratio values for both direction 1 and direction 2, comparing them with the values calculated using the empirical equation.

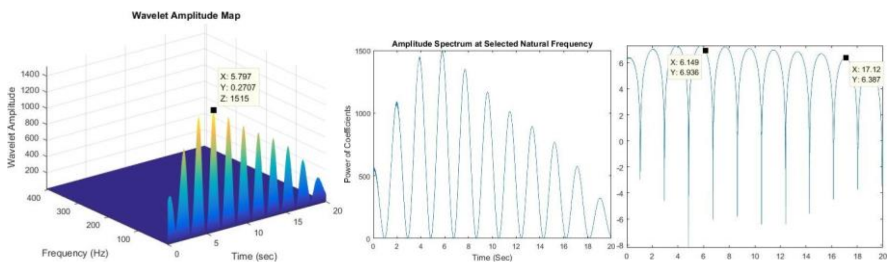

Figure 10: 3D wavelet amplitude map Wavelet envelope and natural logarithm of the wavelet envelope of channel 2.

Table 9: Comparison of damping ratio values from CWT with empirical methods

Code	Damping Ratio (%)			
	Luna Tower		Twin Peakes Tower	
	Direction 1	***Direction 2***	***Direction 1***	***Direction 2***
Eurocode 1	1.57	1.57	1.57	1.57
AS/NZS 1170	0.50	0.50	0.50	0.50
ASCE 7-10	2.00	2.00	2.00	2.00
ISO 4354	1.20	1.20	1.20	1.20
Lagomarsino	2.99	2.79	2.49	2.55
Using CWT	2.23	1.67	2.66	1.81

4. Conclusion

In this paper, the natural frequencies and damping ratios of the first mode in two high-rise RC structures were evaluated. Acceleration data was collected using accelerometer sensors and analyzed. The computational time was reduced using the random decrement method on ambient signals. The normalized ambient vibration signals were then analyzed using Continuous Wavelet Transform (CWT) and Fast Fourier Transform (FFT).

In Luna tower, the first mode natural frequencies were 0.26 Hz (FFT) and 0.25 Hz (CWT) in direction 1, and 0.26 Hz (FFT) and 0.27 Hz (CWT) in direction 2. CWT results showed good agreement with FFT. Compared to empirical equations, all methods except ASCE 7-10 aligned well. Damping ratios for the 1st mode were 2.23% (direction 1) and 1.67% (direction 2). Notably, the literature's damping ratios differed significantly from CWT estimates.

In Twinpeak tower, the first mode natural frequencies were 0.30 Hz (FFT) and 0.29 Hz (CWT) in direction 1, and 0.31 Hz (FFT) and 0.30 Hz (CWT) in direction 2, showing good FFT-CWT agreement. Except for ASCE 7-10, all methods are closely aligned with literature values. Damping ratios were 2.66% (direction 1) and 1.81% (direction 2). Notably, CWT estimates differed significantly from the literature's values.

When comparing the estimated natural frequency values with the FEM results, it is observed that they are higher than the FEM results. This disparity can be attributed to dynamic analysis, where the total mass considered comprised the dead load and 25% of the equivalent mass due to the imposed load. However, it's important to note that during the measurement, the building was not under fully operational conditions, which contributes to the difference. It is anticipated that when the building is in a fully operational state, the natural frequency values will decrease, aligning more closely with the FEM results.

In conclusion, this research represents a significant advancement in the field of structural engineering, offering a practical bridge between theoretical models and real-world applications. The empirical validation of natural frequencies and damping ratios, coupled with innovative methodologies like Continuous Wavelet Transform (CWT), sets a new standard in the assessment of tall buildings. The study's focus on real operational conditions and its regional relevance in the context of Sri Lanka's construction boom makes it not only timely but also crucial for the local engineering community. Furthermore, the initiative to develop a comprehensive database for tall buildings in Sri Lanka signifies a pioneering effort, providing a valuable resource for future research and practical applications. This research not only enriches our understanding of structural dynamics but also lays the foundation for further advancements in the field.

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URBAN LANDSCAPE ECOLOGICAL PLANNING SESSION

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THE ROLE OF COMMUNITY PARTICIPATION IN DISASTER RISK REDUCTION INITIATIVES WITH SPECIAL REFERENCE TO THE BATTICALOA CITY

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Abstract: Human beings as pioneering creatures have trailed novel behaviors in which to mitigate the awful effects of disasters. Anyhow, for years human behavior regarding disasters has been responsive to nature. Communities are occasionally aware of the hazards that they encounter, and they could wait in anticipation of a disastrous incident and then activate approaches and activities. Disaster risk reduction (DRR) has become a strategy precedence worldwide and in line with this movement, the Sri Lanka Disaster Management Act and National Disaster Management Plan prioritize DRR in efforts to develop resilient communities with local municipalities being essential to build their own Disaster Management Agendas. The issue is that community participation is treated as of subordinate significance yet international agreements such as the Sendai Framework for Disaster Risk Reduction dynamically endorse community participation in DRR. A bottom-up approach is the most active in safeguarding effective DRR initiatives at the local scale since communities take possession of these initiatives and obtain a better empathy for their risks. Community-based disaster risk reduction initiated in the paradigm moves away from the contemporary disaster management method, moving away from responsive comebacks in the top-down approach in disaster risk management to more proactive responses. This research study discovered approaches used for community participation to safeguard effective DRR initiatives in Batticaloa City. The study is exploratory and descriptive, having used qualitative and quantitative research approaches, which included a participatory approach. The results assembled from the data recommended that the role of community participation in DRR initiatives is effective in Batticaloa municipality because of the willingness of stakeholders to participate in DRR. Accordingly, it was recommended that community participation sessions should be conducted to create resilient cities and challenge climate change in the future.

Keywords: Climate change; Community participation; Disaster risk reduction; Participatory approach; Resilient cities

1. Introduction

Disasters are thought to be local incidents because ‘local communities are on the leads of both the direct effect of a disaster and the preliminary tragedy response to a disaster’ (Shaw 2012:4; UN/ISDR 2007a: iii). Increased collaboration between disasters and communities has highlighted the significance of local establishments inspiring and supporting vulnerable communities to shape their managing capacity even though the community should be at the main of all answers that are distributed. The adoption of frameworks such as the Yokohama Strategy and Plan of Action for a Safer World, the Hyogo Framework for Action, and the Sendai Framework for Disaster Risk Reduction (SFDRR) have emphasized the vital of authorizing communities to condense their disaster risks. Community-based disaster risk reduction (CBDRR) stipulates an answer to the increased disaster risks within communities, as it intends to reinforce and enable communities to ‘take on any programs of growth including disaster preparedness and mitigation’ (ed. Shaw 2012:5). Though, it is significant that communities have their own belongings and social connections in addition to their efforts to take part in DRR activities, because a lack of possessions and social connections may hinder their partaking effectiveness (Allen 2006:84).

1.1. Objectives of the research

- To identify vulnerable areas exposed to the disasters in the Batticaloa Municipal Council area.
- To examine how the local community actively participates in the disaster risk reduction initiatives process.

1.2. Research question addressed in the study

- How local community contribute to the disaster risk reduction process in the Batticaloa Municipal area?

2. Literature review

The social capital theory, which is ‘about the worth of social connections, attachment alike people and linking between varied people, with customs of reciprocity’ (Claridge 2004) is a suitable theory that reinforces CBDRR since they are both concerned with inspiring the contribution of local people in recognizing and resolving problems in their societies (see Figure 1). The social capital theory allows individuals and/ or assemblies through communal action to grasp required consequences (Silici n.d.:2). The theory also endorses a sense of belonging, respecting variety in others and similar life chances (Babbie 2007:11).

The community-based approach in wide-ranging highlights the significance of the community, together as key players in and primary recipients of an initiative (Lassa et al. 2018:1–2). Therefore, it is vital when working with a community-based theme to repetitively ask ‘what is the community?’ in the query (Petal et al. 2008:193). Even though communities are heterogeneous for the reason of gender, age, experience, culture, leadership styles, and religion, every person must be treated equally. It is, therefore, vital to repetitively identify features such as geography, culture, community representatives (Do they exist? Have they been chosen? Selected or hereditary?), who is presumed to contain the community (by themselves and others), and who is marginalized from the community. Although there might not be conclusive answers, these queries do support thoughtful the diverse opinions and features of communities, communities within communities, and areas of societies (Girvan & Newman 2002:7821).

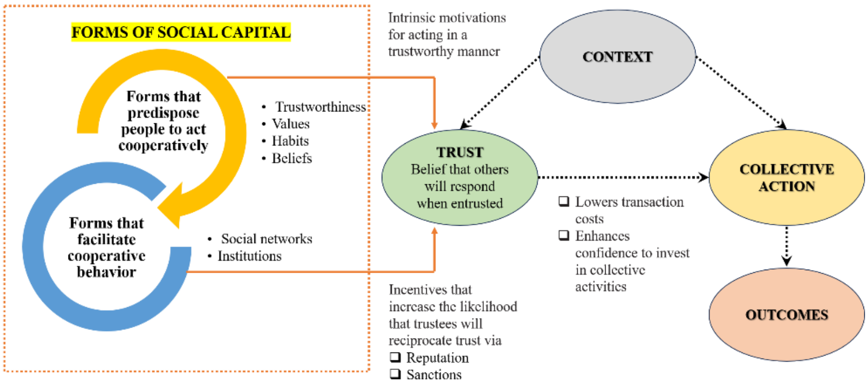

Figure 1: Conceptual framework showing how forms of social capital generate collective action.

Community-based disaster risk reduction could authorize marginalised persons (Chambers 2012) though a local emphasis often stops to unite effects from sophisticated levels (Scoones 2009). Therefore, plans are inclined by community associates' narrow knowledge of local drivers and their direct needs and are controlled by their limited supremacy (Conway & Mustelin 2014).

According to Abarquez and Murshed (2004), CBDRR instigated the paradigm shift away from the conventional disaster management method. This shift encouraged the importance of being motivated away from the structural methods to the more non-structural methods, thus inferring a move away from the responsive retorts in the top-down approach in disaster risk management to more proactive responses (Scolobig et al. 2015:202). Shaw (ed. 2012:4) recommended that community-based disaster-based actions occurred more than 100 years ago where people could take care of each other to reduce damages or harm that occurred by disasters.

After the failure of government-based DRR initiatives planned to address the requirements of persons and communities, CBDRR initiatives began to receive acknowledgment at both the national and local levels of government (Phiri 2014:29). The development of CBDRR began with community-based disaster management (CBDM), which progressively changed into CBDRM and then into CBDRR (ed. Shaw 2012:4).

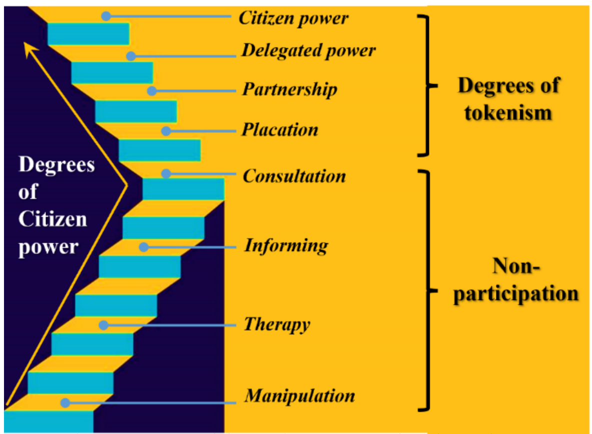

Figure 2: Ladder of community involvement.

Community-based disaster management became popular during the 1980s and 1990s because of the failure of the conventional disaster management method to address the requirements and main concerns of societies and to reduce their vulnerability to disasters. The final had been mainly because of the use of a top-down method (Phiri 2014:27).

Community-based disaster risk reduction is a procedure of DRR that places noteworthy prominence on community participation, mainly because communities themselves are directly affected by disasters and the CBDRR also entails the collaboration of institutions and organizations in sectors such as health, agriculture, education, and infrastructure development. This procedure was accepted because of the failure of disaster risk management to place societies at the center of decision-making. In the disaster risk management method decisions were made by government officials based on their insight of the requirements of communities (Scolobig et al. 2015:203). This would be denoted as the use and therapy level in community participation in Sherry Arnstein's (1969) Ladder of Citizen Participation (see Figure 2).

3. Research methodology

Looking into the perspective of the research flow; as a preliminary stage identification of the research problem, identification of the research objectives and scope of the research were identified. A second stage which is composed of a theoretical framework was done with the literature survey concerned with a review of social capital theory, community-based approach, and community-based disaster risk reduction. As a third stage empirical case study analysis was carried out for the Batticaloa Municipal Council area by qualitative and quantitative research approaches process. Finally, a conclusion and recommendations were derived.

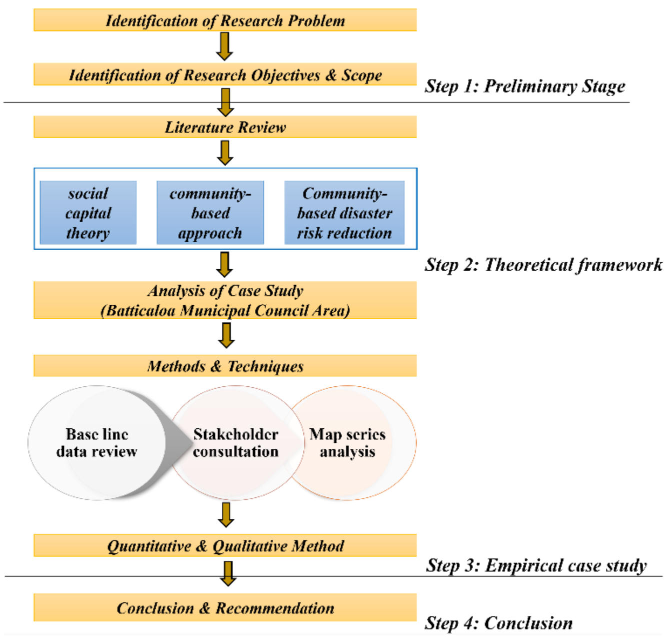

Figure 3: Flow of the research.

Background data and stakeholder consultations were adopted as a base to conduct numerous assessments.

- A Hazard Assessment to consult the community on the nature of the hazards they encounter and where they occur.

- A Vulnerability and Risk Assessment to assess the city's vulnerabilities to disasters (physical, social, economic, and environmental) and how hazards and vulnerability occur, as well as to identify high-risk areas.
- A strategic SWOT analysis to evaluate to evaluate the Strengths, Weaknesses/Limitations, Opportunities, and threats involved in the process of achieving resilience in Batticaloa.
- A comprehensive problem analysis to identify problems, root causes, and severity, as well as to assist in prioritizing problem-solving.

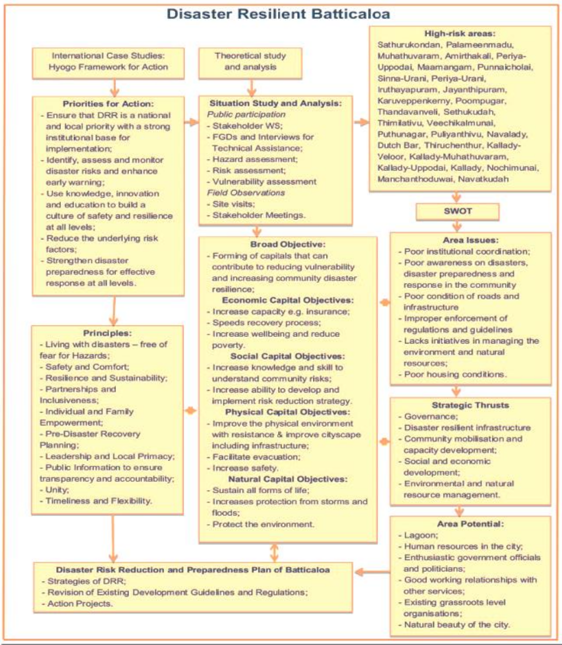

Figure 4: Process carried out to develop strategies and action projects.

Element	Weaknesses
Institutional Set-up	- Lack of coordination between central, provincial and local governments on development initiatives. - Absence of joint projects; rather dispersed operations. - Lack of database management systems among institutions. - Lack of coordination and resource sharing among institutions. - Lack of training and expertise to implement and monitor guidelines and regulations. - Absence of clear guidelines and responsibilities of various organisations - overlapping jurisdictions between UDA, CCD, CEA, DMC, MC, Forest Department, DSD etc. - Lack of technical knowledge about disaster and software in the government and regional officers (Geographic Information System [GIS], remote sensing etc.).
Location and Regional Linkages	- Traffic on roads, lack of pedestrian pathways, and lack of signage when entering city area makes it difficult for new visitors to find places. - Poor conditions of interior roads. - Some parts of the city area are located below mean sea level, therefore facing high risk of flooding. - Low land district compared with adjoining district such as Polonnaruwa, Ampara, Monaragala.
Infrastructure	- Lack of drainage network especially in new developments. - Topographical and geomorphological features are not considered when designing the drainage network. - Absence of sewerage network in the city. - The semi-permanent and permanent houses have difficulties in accessing basic infrastructure such as electricity. - Lack of solid waste management facilities (for both treatment and disposal) in the city leads to indiscriminate dumping of garbage and land pollution. - The surface drains are used for carrying waste water which leads to environmental hazards.
Hydrological system	- Disposal of solid waste into the lagoon pollutes the environment. - People depend on groundwater but groundwater gets polluted due to unavailability of sewer network and salt water intrusion.
Urban Form	- Space for horizontal development is limited due to the geographic setting and the existing railway line corridor. - Concentration of conflicting activities in one place, (need a balance between fisheries and tourism based water activities). - Natural environment blocked by the built environment setting. - Conflict between Administrative Units and archaeological site maintenance (Kachcheri [Government Offices] are located within the fortress). - Sub optimal utilisation of land. - Coastal areas are vulnerable to sea erosion. - Gandhi Park not well utilised and some urban space are not functioning and are under-utilised. - Unauthorised settlements on water bodies (Poompogar) which increase the flood occurrence. - The water table is low.
Disaster	- Inadequate evacuation paths and evacuation centres. - No proper training for the community on DRR. - Lack of community mobilisation initiatives on DRM. - Lack of proper database management in DRR Management. - Lack of preparedness and infrastructure facilities.

Figure 4: SWOT analysis-Weaknesses.

Element	Strengths
Location & Regional Linkages	- Batticaloa is strategically connected with various economic nodes of the country and is a regional service centre for the south eastern coastal area. - Existing circulation patterns and linkages, good pedestrian orientation within the city centre. - Capital of Eastern Province, core centre for tourism (to the north is Passikudha and south is Oluvil and Arugam Bay).
City Economy	- The city's economy is enjoying a period of high growth following the end of the war in 2009. The service sector which comprises tourism, fisheries, commercial activities, institutional, health, and transportation, are the major contributors to the city's economy. - Being strategically located close to the sea and the lagoon facilitates the fisheries industry while sandy beaches enhance the scenic value of the city. - There are major types of wholesale and specialised markets in the city which enhance the regional importance of BMC. The fruit and vegetable market and the fish and meat market of BMC are the major distribution centres for adjacent localities. - The city is gaining importance as a centre of retail trade. - Poultry industry, coconut and cashew plantations and dairy products can also be identified as the other economic activities that are dominant in BMC area.
Image and Identity	- The redevelopment around the lagoon in the city centre has provided a central place for community gatherings and for leisure and recreational activities. The city gate and the beaches add to the city's identity. - The city centre functions as a destination with amenities such as hospitasl, churches, library, schools, parks and administration services that bring people to the centre.
Tourism	- The city attracts domestic tourists. - Connectivity to other tourist destinations such as Passikudah, Arugam Bay and Polonnaruwa archaeological site.
Institutional setup	- Presence of a number of development bodies and NGOs.
Infrastructure	- After the war, main roads were repaired, increasing accessibility and connectivity. - Availability of teaching hospital and other health institutions. - Availability of schools and other social infrastructure facilities.
Urban Form	- Flat terrain of BMC facilitates the growth of the city. - High connectivity to the city centre (Bus stand, commercial activities, hospital). - Development along main linear roads provides easy access to the public.
Hydrological system	- Interconnected hydrological system with lagoon, sea and *thonas*. (*Thonas* are small water bodies located on the coastal sand line that drain to the sea when overflowing.) - Natural anchoring place.

Figure 5: SWOT analysis-Strengths.

Element	Opportunities
Economic competitiveness	- Good connectivity can influence development as a nodal centre linked with other economically vibrant cities such as Trincomalee, Polonnaruwa and Ampara. - BMC can attract many tourists because of its rich heritage, culture and environmental setting and peaceful places for religious reflection. - Due to good connectivity and urban form, BMC can attract developers in tourism, business and infrastructure sectors. - City has the potential to build upon the existing business mix and promote tourism related industries.
Proposed Projects	- Disaster Resilient City Development Strategies for Sri Lankan Cities Project. - Proposed sewerage treatment plant. - Beautification projects. - Coastal resources management programme. (Coastal Conservation Department). - Proposed extension of domestic airport in the city. - Reconstruction of Kallady Bridge.
Hydrological system	- Lagoon could be used to divert the flood in the city. - Water based transport system.
Urban form	- Potential for vertical development. - Urban area has potential for compact development. - The lagoon and natural beauty of the city to be promoted for tourism based industries. - Potential for waterfront development.

Figure 6: SWOT analysis-Opportunities.

Element	Threats
Economic	- Lack of adequate infrastructure to capitalise or attract economic opportunities.
Infrastructure	- Lack of sewerage system, solid waste management, poor distribution of water, and ground water pollution which can cause health problems and unhygienic conditions in the city. - Infrastructure provision in the low income houses is inadequate resulting in very poor living conditions. - The perception of traffic and lack of parking could impede development activity and location of new businesses in the city centre. - The city and other utility providers such as CEB, NWSDB are hesitant to offer under-grounding of utilities due to costs and maintenance issues. These issues could threaten the ability to improve the overall appearance of the streetscape and city beautification.
Institutional arrangements	- Urban Development is the responsibility of all three levels of government. These overlapping roles have led to a non-functional executive system of the city. - Degeneration of interior and surrounding residential areas, particularly as it pertains to property maintenance, also presents a threat to image.
Mangroves and Ecosystems	- Destruction of mangroves due to security reasons, fuel wood and fishing. This leads to some of the other problems such as: - Breeding places for prawn and crab are being destroyed. - Reduction of migrant birds, affecting both the biodiversity and the emerging eco-tourism activities in the area. - Eco-systems being destroyed. - Loss of natural green spaces.
City Economy	- Illegal fishing and prawn farming creates over-fishing and possibilities of lagoon pollution
Strategic Location	- The city is located in a highly vulnerable zone, exposed to cyclone and tsunami.

Figure 7: SWOT analysis- Threats.

The assessments used an analysis of the baseline information and a series of interviews and workshops with stakeholders, including local communities and institutions, civil society, government, the private sector, development partners, and academic professionals. The assessments produced a series of maps indicating risk levels relating to hazards identified by the community.

Figure 8: Photographs of community participation.

4. Analysis

4.1. Background of the case study area

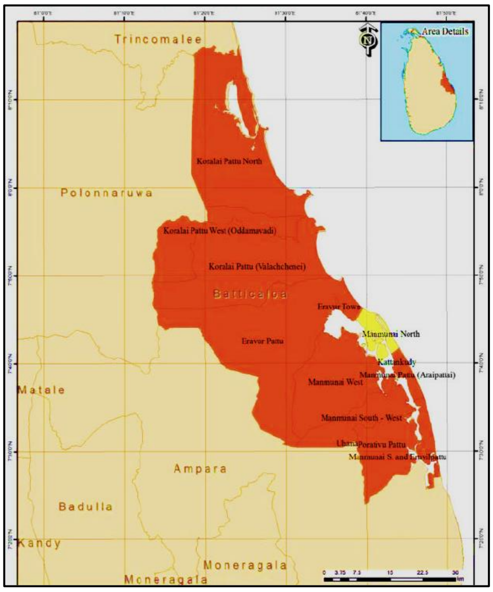

Figure 10: Case study area-Batticaloa Municipal Council area.

Batticaloa is a main city in the Eastern Province, of Sri Lanka. It is the administrative capital of the Batticaloa District. It is on the east coast, 111 kilometers south of Trincomalee, and is situated on an island. Since Batticaloa district is vulnerable to disaster and for this research, the main urban center of the Batticaloa District which was Batticaloa Municipal Council was selected as a case study area.

From the number of flood events that occurred in the country from 1974- 2008, Batticaloa district consists of a higher flood limit. Vulnerability assessment conducted by the faculty of architecture, University of Moratuwa to formulate a city development strategy for a Sri Lankan city to respond to climate change (2010) analyzed 40-year records of meteorological data of Batticaloa Municipal Council. The rainfall data of this analysis revealed a strong trend of monsoon rainfall increase (28% in Batticaloa Municipal Council) and a corresponding increase in the occurrence of minor floods. The population of the case study area was around 92,000 and the extent of the land was about 75.09 sq. km.

4.2. Community-based hazard mapping

Natural hazards identified by stakeholders include floods, tsunamis, sea level rise, and cyclones. The location where each hazard is likely to occur is presented in below mentioned figures Community Mapping-Flood Hazard, Community mapping-Tsunami Hazard, and Community mapping-Sea Level Rise

Hazard. Cyclones were harder for the community to map so Cyclone Map is obtained from the Metrological Department.

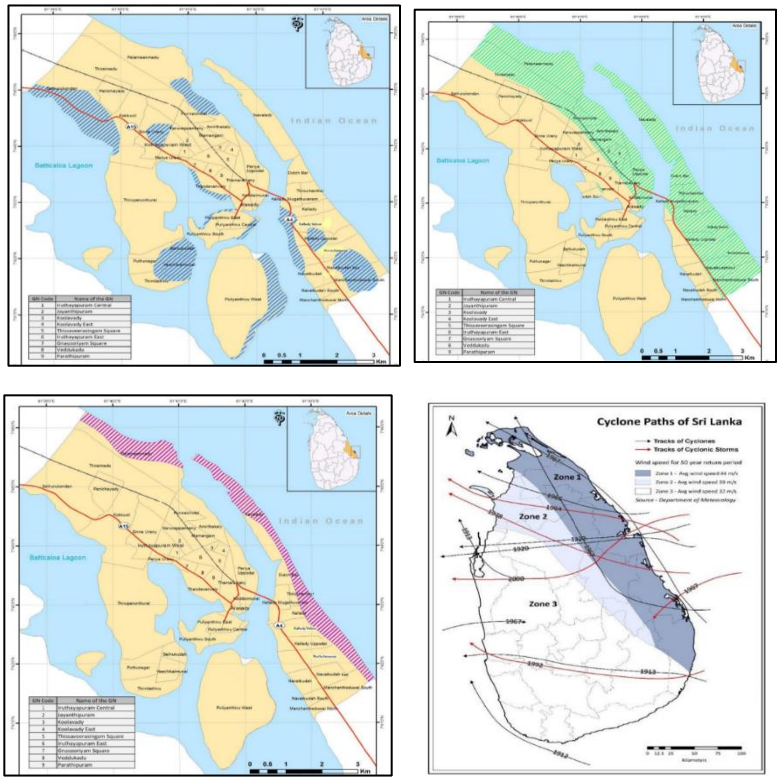

Figure 9: Community mapping-flood, Tsunami, Sea level rise and cyclone.

4.3. Vulnerability and risk assessment

The vulnerability and risk assessment were focused on building knowledge of hazards faced by the community. The data gained through the community-based hazard mapping was then combined with information collected through the baseline analysis including details on the demographics, technological and socio-economic conditions, unplanned urbanization, development in high-risk zones, under-development, environmental degradation, climate variability, climate change, geological hazards, completion for scarce resources and the impact of epidemics. The objectives of the vulnerability risk assessment were:

- To identify hazards and hazard-prone areas while assessing the vulnerability of each city element to the identified hazard.
- Analysis of the consequences of the hazard and potential disasters.
- Identify high-risk areas, understand the background, and propose strategies for disaster-resilient cities.

4.4. Multiple hazards and risk levels

Finally, a multiple-hazard risk map was prepared to identify areas that have the highest risk levels based on multiple hazards. This was prepared by amalgamating all four risk maps (flood, tsunami, sea level rise, and cyclone). 7 zones were identified within the Batticaloa Municipal Council area. It is essential to formulate and implement tailored strategies to mitigate hazards that are specific to each area.

Table 1: Identified risk zones in Batticaloa Municipal Council area

Risk zone	Name of the area	Type of the hazard
1	Sathurukondan	Flood and cyclone
2	Palameenmadu, Mugathuwaram, Amirthakali, Periya-Uppodai, Maamangam, Punnachcholai	Flood, Tsunami and Cyclone
3	Sinna-urani, Periya-Urani, Iruthayapuram, Jayanthipuram, Karuveppenkerny, Poompugar, thandavenveli	Flood and Cyclone
4	Sethukudah, Thimilathivu, Veechukalmunai, Puthunagar	Flood and cyclone
5	Puliyanthivu	Flood and cyclone
6	Navalady, Dutch Bar, Thiruchenthoor, Kallady-Veloor, Kalldy-Mugathuvaram	Flood, Tsunami and Cyclone
7	Kallady-Uppodai, Kallady, Nochchimunai, Manchanthoduvai, Navatkudah	Flood and cyclone

4.5. Strategic directions for a resilient city

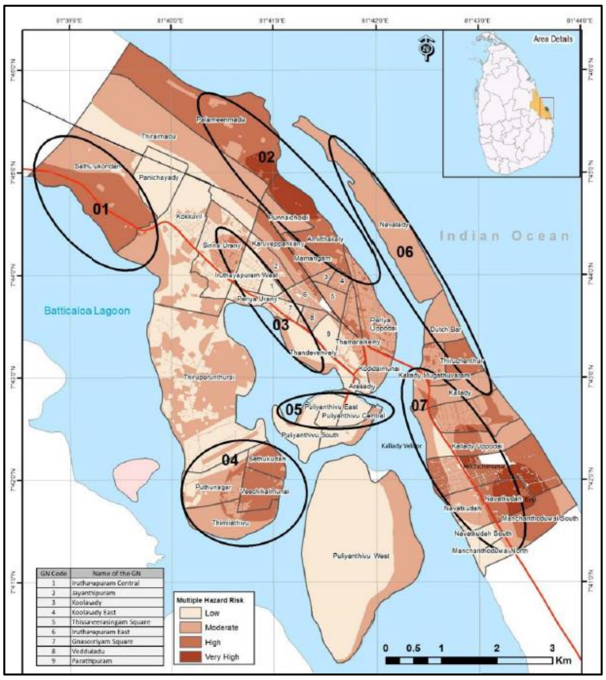

Figure 10: Composite hazard risk map.

In developing the Batticaloa Disaster Risk Reduction and Preparedness Plan, the baseline study, and assessments provide a solid and valuable foundation for developing the city's vision and disaster-resilient strategies. They all include the community, as well as community groups, city employees, and council members.

Batticaloa is a city that is growing in terms of attracting commuters and tourists. It is a base for a growing number of business activities and is a regional service center. The Batticaloa Municipal Council must increase its capacity to plan and manage the future sustainably. Disasters have previously halted this growth and caused severe damage including hardship for the population. The Batticaloa Municipal

Council must develop two important tools to manage hazards; 'Resilience Strategies and 'urban Planning Strategies incorporated with DRR. The 5 strategic directions developed for this case study area.

- Improve the built form of the city.
- Integrating social and economic development
- Strengthening environmental and natural resource management
- Community mobilization and capacity development
- Improve city governance and disaster management.

5. Conclusion

Community participation is one of the keystones of active DRR. Although community participation is one of the keystones of effective DRR and there are strategies and/or plans in place, communities in high-risk vulnerable zones are frequently accepted from the formal decision-making progressions regardless of the circumstance that disaster hazards have been exaggerated by the intensification in vulnerabilities associated to underdevelopment and climate unpredictability, among all.

The information collected recommended that community participation in DRR initiatives in Batticaloa was focused mainly on notifying and accessing the community. The initiatives that have been implemented are fixated on delivering understanding and awareness to communities. Furthermore, it was realized that the participants (stakeholders) did not fully comprehend their roles or how they fit into disaster risk management. This was recognized because some of the respondents mentioned the investigator to the Disaster Management Centre when they heard the term DRR as they were under the brand that they did not have a protagonist to play in DRR. It is, therefore, significant that all stakeholders be knowledgeable of their protagonists using a stakeholders' meeting because it is authoritative that all stakeholders contribute if disaster risks are to be successfully reduced.

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THE ROLE OF CULTURAL VALUE IN SUSTAINABLE URBAN DEVELOPMENTS WITH SPECIAL REFERENCE TO THE FLOATING MARKET IN PETTAH

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Abstract: Urbanization is a global trend. In emerging nations like Sri Lanka, the non-visionary authorities have been attempting to replicate every eye-catching space they observe in other countries without incorporating it into our local culture. There are several examples of alienated urban developments that have become unsustainable built environments today in Sri Lanka. In terms of culture, planning for sustainable development entails more than just a typical roof or a symbol. It is the result of a coordinated effort involving correct planning in economic sustainability, environmental sustainability, and social sustainability. The floating market in *Pettah,* designed to promote both foreign and local tourism, has lost its appeal due to a lack of cultural offerings. Because In Sri Lankan history, there have never been any floating markets, and locals don't have any particular preference for using them. Cultural tourism is a key trend in encouraging sustainable tourism, but since there are no offerings in the market that accurately capture the spirit of Sri Lankan culture for foreign tourists, they don't find the market attractive like authentic floating markets In Southeast Asia. The market, which initially attracted crowds, has now been abandoned due to insufficient earnings, and a few stalls remain lucrative. In the future, we should steer clear of such urban idiocy. The research design aims to conduct the research in a sequential sequence of relevant steps to follow up on a standard research method to test the hypothesis by following the research objectives by generating a research framework from a Literature review, analyzing strengths, and weaknesses in major and minor case studies according to the research model, and assessing the results using a weighted analysis within their cultural base. The research findings have proposed the need to integrate cultural foundations into urban developments to make them a successful endeavor.

Keywords: Culture; Floating markets; Sustainability; Urban developments

1. Introduction

1.1 Research Background

Sri Lanka has been urbanizing since 1977, with non-visionary authorities attempting to replicate foreign developments without considering their suitability. The floating market in *Pettah* (FMP), inspired by Southeast Asian countries like Thailand, Indonesia, and Vietnam, is an example never found in Sri Lankan history. This research examines the unviability of the first-ever floating market in Sri Lanka, built as part of the Bastian Canal development project, emphasizing the need for sustainable urban developments that consider people's culture.

The floating market area was an abandoned factory and ruins a decade ago. The government subjected it to a canal-based development as a Floating market (*Gunatilleke*, 2019). The floating market aimed to attract tourists by offering local items and crafts, enhancing the region's appeal to foreign and local tourists, and fostering a local atmosphere for shopping.

Floating markets, first developed in Southeast Asian countries like Thailand, Indonesia, and Vietnam, have been sustainable for over 100 years, attracting foreign tourists to explore traditional cultures. However, despite being reopened after five years in Sri Lanka, ¾ of the stalls are closed due to lack of visitors. Despite this, other Southeast Asian countries' traditional floating markets continue to attract tourists.

1.2 The Big Question

"Which explains the causes of the tourist boost during the market's initial implementation, but now not at the *Pettah* floating market?" Once a popular tourist destination, the market is now experiencing isolation due to a lack of visitors; the overall picture depicts its unsustainability as an urban development.

1.3 The Research Question.

The Sri Lankan lifestyle has traditionally relied on open square or enclosed shops, but introducing floating markets sparked excitement and a rush to explore new things. However, this excitement is only sustainable if it represents our cultural habits, leading to a loss of interest in revisiting. Foreign tourists often seek cultural tourism, allowing them to explore and experience indigenous and contemporary cultures. A destination must fulfill this to be a unique tourist destination, hindering economic growth and engagement. Colombo faces a common issue where different contexts, such as larger rivers, cities, geography, and cleaner waters, inspire interventions. Decision-makers often choose bland duplicates to replicate the perceived success of another site, which is often out-of-scale and likely to fail. The research aims to find the answer to the following question. "Is the floating market in *Pettah* unsustainable because it does not play the role of local culture?"

1.4 Research Hypothesis

In the contemporary world, global initiatives link culture to sustainable development. (*Munasinghe*, H, 2016). The United Nations Educational, Scientific and Cultural Organization International Conference on "Culture" for Sustainable Cities and the Subsequent Outcomes (2015) identified Culture and cultural heritage as practical in aiding the New Urban Agenda's goal of making cities. Since Culture has great significance in developing and regenerating urban developments, the hypothesis is "The lack of a city's cultural role in urban developments may lead to its non-sustainability."

1.5 Introduction to Case Studies

The research has **03 Minor case studies** and **01 major case study**.

<u>Minor case studies</u>

Floating markets are prevalent in Thailand. Their traditional floating markets evolved 100 years ago and are now famous tourist traps. Therefore, the Thai Tourist Authority looked for new floating markets.

From 1990 to 2000, the Thai government introduced floating markets as a tourist development in selected country areas. (*Chalermpat Pongajarn, René van der Duim & Karin Peters*, 2016, P.1). Minor case studies are such floating markets imposed by the government that have a high tourist attraction. (Not authentic traditional markets) as tourist developments, similar to Sri Lanka's FMP, an urban development imposed by the government.

1. *Amphawa* Floating Market (AFM)
***2. Tha Kha* floating Market (TFM))**
***3. Bang Namphueng* Floating Market (BFM)**

Major case study

The Floating Market in *Pettah* (FMP) is the major case study which is the first and only floating market in Sri Lanka, which is doomed to be a failure at the current stage.

1.6 Goals & Objectives

The main goal of this research is to assess the role of culture in the sustainability of urban development using major and minor case studies. The main objectives are

1. To generate the research framework from a Literature review on the role of culture in sustainable development.
2. To analyze strengths and weaknesses in minor case studies according to the research model.
3. To analyze strengths and weaknesses in the major case study according to the research model.
4. To assess the Strengths and weaknesses using an analysis of weighted strengths and weaknesses and measure the impact of culture on their sustainability.

1.7 Scope & Limitations

Since the FMP is the only one of its kind, the local case study will be limited to one case study, and it is the major case study: FMP. Minor case studies from Thailand were chosen due to their success in sustainability, based on literature reviews, and not traditional floating markets, demonstrating the Thai government's commitment to sustainable development.

2. Literature Review

The literature review consists of three parts: Discussing the significance of culture in sustainable urban developments, the history and evolution of traditional floating markets in Thailand and Addressing research gaps.

2.1 Significance of Culture in Sustainable Urban Developments

It is implied in the study (Glen Hole, 2020) that sustainability aims to meet current human desires without compromising future generations' ability to meet their own.

Cultural Tourism [(1).]

Conceptual Definition- The movement of people to cultural attractions away from their usual place of residence to gather new information and experiences to meet their cultural needs.
Technical definition- all movements of people to specific cultural attractions such as heritage sites, artistic and cultural manifestations, arts, and theatrics that are not in their usual place of residence. (Ashworth (1995), Richards (1996)

Culture is crucial in sustainable development, shaping people's attitudes towards the built and natural environment and affecting all operations. He also indicated the impact of culture on three pillars of sustainability as follows.

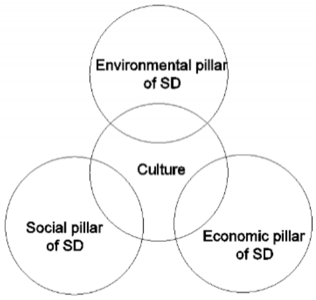

Figure 1: Impact of Culture on three pillars of sustainability.
Source: Glenn Hole (2020)

In 1996 "City Summit" at Habitat II (2) also highlighted the importance of culture in urbanization, emphasizing its role in promoting well-being and diversity in cultural heritage and values**.** *Dessein et al.*, (2015) presented the three conceptual models of culture for Sustainable Development.

1. **Culture in Sustainable Development**
2. **Culture for Sustainable Development**
3. **Culture as Sustainable Development**

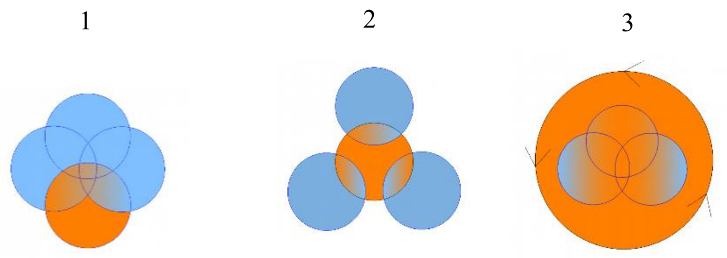

Figure 1: three conceptual models of culture for sustainable development.
Source: Glenn hole (2020)

Nancy Duxbury, *Jyoti Hosagrahar*, and *Jodi Pascual* (2021) suggest that culturally connected urban development fosters collaboration, ownership, and a sense of belonging among residents. This gendered and culturally conscious approach improves individuals and communities, promoting a more inclusive and sustainable urban environment. *Munasighe* (2016) emphasizes the importance of integrating culture into urban planning for revitalizing urban space and the economy. *C. Mercer* (2016) highlights cultural planning as a culturally sensitive approach to policy and planning, focusing on strategic and holistic utilization of cultural resources for urban and community development.

2.1.1 Thematic categories of pillars of sustainability

Denis Michalina, Peter Mederly, Hans Diefenbacher, and *Benjamin Held* (2021, P.9) Presented the most frequently used thematic categories within the selected frameworks of social, cultural, and economic pillars of sustainability.

The "City Summit" at Habitat II [(2)]

On June 3-14, 1996, the United Nations held Habitat II, also known as the City Summit, in Istanbul, Turkey. The conference was the final in a series of UN conferences held over the last decade to address pressing issues confronting the global community in the twenty-first century. Habitat II, which addressed urbanization issues, took place 20 years after the first Habitat conference, which focused on urban and rural housing issues in Vancouver, Canada.

Table 1: thematic categories within three pillars of sustainability

Pillars of Sustainability	Thematic Categories
`Environmental Sustainability	Water
	2. Mobility and transport
	3. Waste management
	Air quality
	Energy
	Land Use
	Climatic Change
	Co_2
	Noise
	Biodiversity
	Environment
	Natural Disaster
	Ecological Footprint
	Soil
` Economic Sustainability	Economy
	2. Employment
	3. Global Appeal
	Economic Structure
	Materials and Products
`Social Sustainability	Education
	social inclusion
	Health
	Housing
	Safety and Security
	Equity
	Social infrastructure
	Social infrastructure
	Public space
	Technology and innovation
	Wellbeing
	Demography
	Poverty

Source: *Denis Michalina, Peter Mederly, Hans Diefenbacher* and *Benjamin Held* (2021, P.9)

In the study of *C. Mercer* (2016), he adapted a table of contexts from Partners for Livable Communities and how arts and culture would impact the following contexts in urban developments.

Table 2: What culture can do a context?

Context	What Arts & Culture Can Do
Restructuring of the Business Community	Bringing to prominence the strategic significance of intellectual property-based cultural and creative (content) industries in urban business communities.
	Help to develop new marketing and branding practices for exciting/ Traditional businesses.
	Work in partnership and synergy with existing/traditional businesses to enhance footfall, offer, branding, and opportunity for consumption and diversity of experience.
`Importance of quality of life and quality of place factors in location decisions	Influence personal/career location decisions
	Influence business location decisions
	Influence inward investment decisions

Context	What Arts & Culture Can Do
Reduction of "sub-urban flight"	Make and consolidate downtown areas more attractive for work and residence.
	Enhance the potential of the evening economy /24-hour economy.
	Encourage renovation of industrial/heritage/ Historical districts.
	Develop human and social capital – skills, trusts, reciprocity, and networks.
	Create busier and safer streets through animation and related strategies.
City-regions – not just facilities	Establish a distinctive sense of local/regional identity and "brand" of products as in the example of "design" in the *Barcelona/Catalunya* city region or the Milan City region. It is the city region that is and always has been the basic unit of economic innovation and value-adding.
Need for a highly skilled workforce	Provide range and quality of amenities to attract highly skilled, high value-added, and knowledge-intensive workers
The Digital imperative for infrastructure and content	Create, exploit, and discriminate the "content" of the cultural and creative industries
	Establish a distinctive brand and niche for the urban area/city region
	Create the synergies between "art" and technology for high-growth sectors such as games and leisure software.
The importance of clusters and networks	Provide the elements of urban "critical mass" and the occasions and venues for creative networking.
	Create "non - non-functional" and informal networks such as "First Tuesday" and "Café Culture" initiatives which bring together creators, producers, consumers, and investors to develop the industry base and market.
Social Inclusion	Demonstrate the positive relationship between cultural diversity
	Ensure that urban cultural strategies do not result purely in gentrification and "ethnic" cleansing
	Increase the diversity of populations, experiences, and footfall (which also means demand and expenditure) in urban centers.

Source*: C. Mercer* (2016, P.4)

2.2 The History and Evolution of Traditional Floating Markets in Thailand

2.2.1 Origin of Floating Markets in Thailand

The study of *Adarsh Batra* (2004) mentions that Thai lifestyle and culture are deeply connected to waterways and river systems, serving as a source of food, navigation, and entertainment. The ancient Thai capital of *Ayutthaya (3)* was renowned as the "Venice of the East" due to its canals and communities. Communities near water bodies utilized rivers for water, rice planting, and commuting naturally and conventionally without road infrastructure.

2.2.2 Thai People and their relation to water.

Adarsh Batra (2014) describes the relationship of Thai people with water, saying that their most critical Thai festivals, such as Thai New Year and *Loy long*, are water-based. A study by *Poomhachai Punparroj* (2010) describes traditional Thai houses in other parts of Thailand as made of wood, mainly teak. The timber flooring of the homes is raised above an accessible height to reduce seasonal flooding.

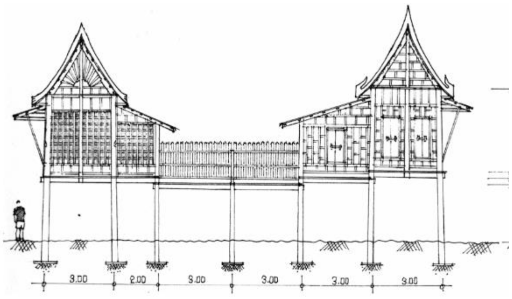

Figure 3: Traditional Thai house.
Source- *Poomhachai punparroj (2010)*

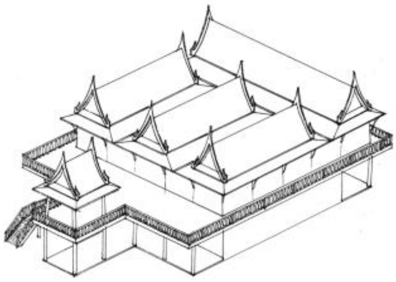

Figure 4: Traditional Thai house.
Source- *Poomhachai punparroj*

2.2.3 Floating markets and tourism

Adarsh Batra (2014) highlights the cultural trend in tourism, with foreigners visiting floating markets to experience different cultures. *Thanya Lunchaprasith and Nethchanok Riddhagni* (2020) suggest these markets attract foreign and local tourists by offering local cultural experiences through traditional commodities, boat excursions, and community interactions.

2.3 Research Gap

There is a significant gap in researched factors of culture-related measures related to the three pillars of sustainability for sustainable built environments, and there is another gap due to inadequate literature on why the country's first and only floating market is doomed to be unsustainable. The hypothesis was tested to determine the cause: absence of cultural role or any other.

3. Methodology

The Methodology aims to conduct the research under a sequential of relevant steps to follow up a standard research method to test the hypothesis via following the research objectives:

3.1 Objective 1 – To generate the research framework from a Literature review on the role of culture in sustainable development.

Dessein et al. (2015) presented three conceptual models showing how culture impacts sustainable development. Of the three models, choose the model demonstrating how culture mediates between social, economic, and environmental sustainability pillars. All three minor case studies in Thailand have used their existing culture as a sustainable development strategy: locals frequently see and know floating markets. As a result, the culture bestows them on all three pillars, benefiting the community.

Ayutthaya[3]

About 80 kilometers north of Bangkok is the Thai city of Ayutthaya. From 1350 until the Burmese destroyed it in 1767, it served as the Kingdom of Siam's capital and a thriving international commerce port. Ayutthaya Historical Park is an archaeological site made up of the old city's ruins that formerly housed palaces, Buddhist temples, monasteries, and statues.

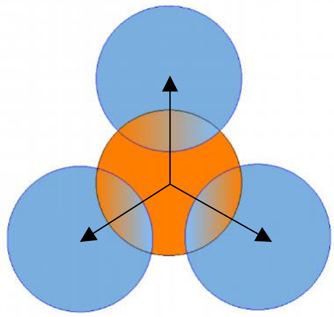

Figure 5: Culture mediates between the other 3 pillars of sustainable development.
Source: *Dessein et al*. (2015)

Next to derive topics for each phase in the research model the themes derived by *Denis Michalina, Peter Mederly, Hans Diefenbacher, and Benjamin Held* (2021) were utilized. (Refer to Table 1) These topics were solely social, economic, and environmental themes. The following sections of the research model are defined as follows.

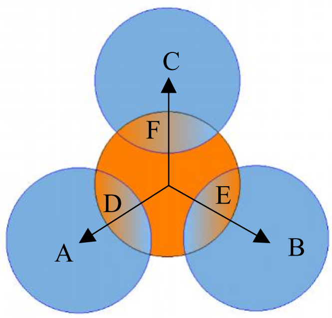

Figure 6: Sustainable Categories
Source: Researcher

A defines socially sustainable Measures, B defines economically sustainable Measures, C defines Environmentally Sustainable Measures, D defines Socio-cultural Sustainable Measures, E defines Economic-cultural Sustainable Measures, and F defines Environmental-cultural Sustainable Measures. Next combined the above Measures with *C. Mercer's* (2016, P.4) findings on what arts and culture can do to each context to derive Socio-Cultural, Economic Cultural, and Environmental-Cultural Sustainable Measures.

Table 3: Socio-cultural, economic-cultural, and environmental-cultural Sustainable measures

Socio- cultural topics(D)	**Economic-cultural topics(E)**	**Environmental-cultural topics(F)**
Attractive public realm Local environmental quality and amenity Decent housing Accessibility Neighbourhood Education and training Social justice Participation and Local Democracy Health, quality of life, and well-being Social capital Safety and security Product Diversity	Cultural sustainability in Building materials Culture for economic sustainability New marketing and branding for traditional business Employment for inhabitants Trickledown effect on poverty Creative industry businesses	Cultural sustainability in Building materials Culture for economic sustainability New marketing and branding for traditional business Employment for inhabitants Trickledown effect on poverty Creative industry businesses

Memory of place Social interaction Sense of community for location decisions Cultural traditions Culture as a rejuvenating development		

Source- Researcher

3.2 Objective 2- To analyze strengths and weaknesses in minor case studies according to the research model.

Collected necessary data from previous literature and verified web sources because these are foreign country examples.

3.3 Objective 3- To analyze strengths and weaknesses in the major case study according to the research model.

Collected data through the researchers' observations, field surveys, and in-person interviews with specific groups such as vendors, local and foreign visitors, and the city's poor. Due to inadequate literature, the study employed mixed methods to improve data accuracy.

3.4 Objective 4- To assess the Strengths and weaknesses using an analysis of weighted strengths and weaknesses and measure the impact of culture on their sustainability.

The internal and external factor analyzing systems (IFAS & EFAS) were presented usually by *Fred R. David* in the book "Strategic Management." According to R. David, both tools recap the results of the company's internal and external environmental analyses. SWOT analysis has to be valued first by how important it is for the development of the place and then by the probability of that particular factor being a strength, weakness, opportunity, or strength. Then the two values multiply and take values. The typical value scopes are as shown below. Only internal factors are considered (Strengths and weaknesses). Omitted Opportunities and threats (External factors) because strengths and weaknesses already exist and are easy to note).

Table 4: Value scope of IFAS (Source: *Fred R. David* (1986)

Internal factors	Weight (how important it is)	Rating (probability)	Weight X Rating
Strengths Weaknesses	0.00-0.05 (highest points) 0.06-0.10 0.11-0.15 0.16-0.20 0.21-0.25 (Lowest points)	5(highest) 4 3 2 1(Lowest)	

Then highlight the most weighted strengths **(Major Strengths)** and weaknesses **(Major Weaknesses),** and if the number of strengths is much greater than the number of weaknesses, neglect the weaknesses and analyze the strengths further. Vice versa then see the type of topic it belongs to in the research model, whether it's a social factor, a socio-cultural factor, an economic factor, an economic-cultural factor, an environmental factor, or an environmental-cultural factor**. If the major strengths and weaknesses are culturally integrated, then they are strengthened by their cultural base or weakened due to the absence of their cultural base.** Then analyze the number of factors belonging to each topic via pie charts to get a quantitative idea of the market's sustainability or unsustainability.

4. Results & Discussion

Results are presented under 54 categories**.**

4.1 Analysis of Total Major and minor strengths and weaknesses in major and minor case studies.

When analyzing the number of total major and minor strengths in each of the major and minor case studies we can compare them as follows.

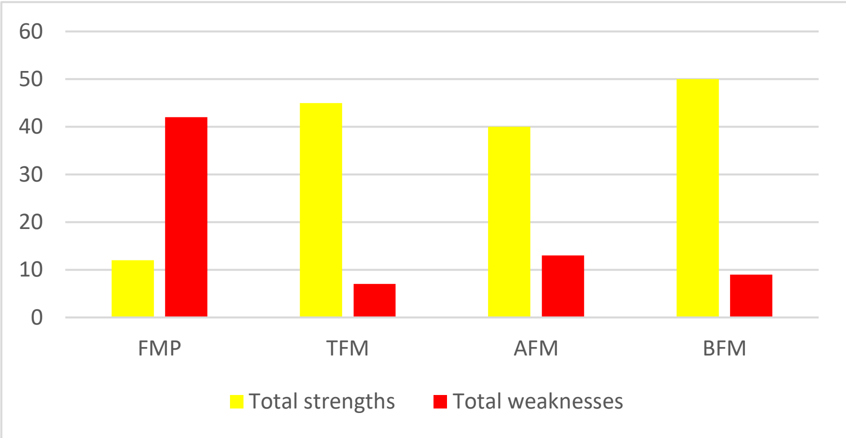

Figure 7: Total Strengths and weaknesses comparison among the case studies. (Source – Researcher)

In FMP, the number of weaknesses is much more significant than its strengths, depicting its unsustainability as an urban development. Therefore, only weaknesses are analyzed. In TFM, AFM, and BFM, the number of strengths is much greater than their weaknesses, depicting their sustainability. Therefore, it disregarded weaknesses from the analysis.

4.2 Analysis Major strengths in Minor Case studies

According to the analysis in **TFM**, a major strength in socially sustainable measures is Having a Publicly accessible open space at the entrance of the market. Major strengths in Socio-cultural measures are Having a unique way of life in communities with nature: village and fruit orchards create a tourism potential, Preserves traditional agricultural lands, Local people's houses near the market transformed into homestay accommodation with slightly modern facilities creating a unique experience for visitors, The presence of walking paths makes pedestrian-friendly events and strengthens the venue as a public space, Having a unique way of life in communities with nature: village and fruit orchards create a tourism potential, Preserves traditional agricultural lands, Local people's houses near the market transformed into homestay accommodation with slightly modern facilities creating a unique experience for visitors, The presence of walking paths makes pedestrian-friendly events and strengthens the venue as a public space, presence of inland waterways integrated with rivers and canals promotes floating architectural events, walkable neighborhoods enhance the connectivity with other public places, Agricultural neighborhoods and traditional houses reflect the cultural identity of the riverside community and make a tourism potential in boat rides, The waterway connects other markets: *Mae Klong* Railway Market so tourists come or go to both destinations via boat rides, Local governments, university students, and organizations visiting *Thaka* for their study trips enhance the market's development, Availability of skilled workforce from families over generations aids in the development of the market, Focal Actors are local government so the state's involvement helps the growth and development of the market, Local people come to buy fresh vegetables and fruits since the market is famous for fresh vegetables and fruits, The local community forms a network of the market committee for the development, The area was known again for a floating market in the venue ensuring the culture's memory of place, Friendly local community interacting with tourists enhances the tourism potential , markets are also used for social meetings by the community, enhancing social interaction, and Use of the riverside community's existing culture to promote tourist attraction; boat ride service enhances the mobility of tourists, giving a new experience; once an agricultural land, again agricultural land does not change the texture of the land, Holding Thai water related festivals as events for tourists enhances the potential for tourism. Major strengths in environmental-cultural measures are Organized negotiation between the local municipality and landlords, which helps the development of the market; the diversity of local products (local dishes and handcrafts) enhances the tourist's enthusiasm; the vendors are from the local community; therefore, the market contributes for the city's economy. Inhabitants are employed at the market, providing them an extra income, rural villagers find their additional payment from the market and the presence of local arts and crafts; the community has a positive sense of their business, ensuring the viability of the market and Using the riverside community's existing culture to promote tourist attractions.

According to the above results, the following chart was prepared, indicating that **69% are socio-cultural sustainable strengths**, **28% are social sustainable strengths**, **3% are economic-cultural sustainable strengths**, and thus **72% of the major strengths are culture-impacted strengths.**

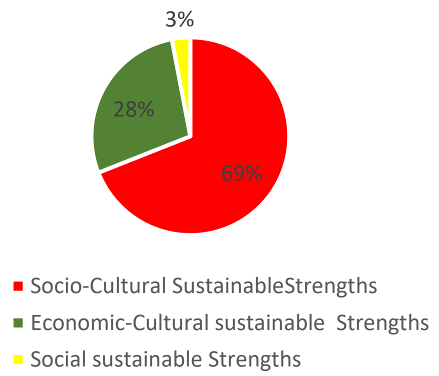

Figure 8: Classified major sustainable Strengths in TFM (Source: Researcher.

According to the analysis in **AFM**, the major strengths in socially sustainable measures are the Presence of open space and well-connected inland waterways. Major strengths in Socio-cultural Sustainable measures are Architecture displaying cultural heritages, Once a waterfront market again into a market, Paying homage to monks by tourists, Presence of good social interaction between the community and tourists, Use of the canal for transportation and trading, Once waterfront stalls now a floating market ensures people's memory of that place, Tangible cultural heritage, and the local community forms a network of the market committee for its development, Waterfront stalls were modified for homestay accommodation to promote sustainability, connectivity with *Tha Kha* floating market, *Damnerns*aduak, and *maekloMae Klonay* market. A major strength in Economic sustainable measures is Tourist promotion via the internet of international tourists. Major strengths in Economic cultural sustainable measures are the Presence of local arts and crafts, other vendors traveling to the market from rural areas to enhance product diversity, firefly boats, Rural villagers finding their extra income from the market, Inhabitants employed at the market, Inhabitants are used at the market, and 60 % of vendors are from the local community, Boat ride service and intangible (performing arts, rituals, music, culinary and way of life, 40% of the vendors are outside from other villages. Major strengths in environmentally sustainable measures are sewage drains, rubbish disposal for safety and security, and the Presence of a Solid waste management system.

According to the above results, the following chart was prepared, indicating that **42% are socio-cultural sustainable strengths**, **38% are Economic-Cultural sustainable strengths, 8% are social and environmentally sustainable strengths, and 4% are economically sustainable strengths; Thus, 80% of the significant strengths are culture-impacted strengths.**

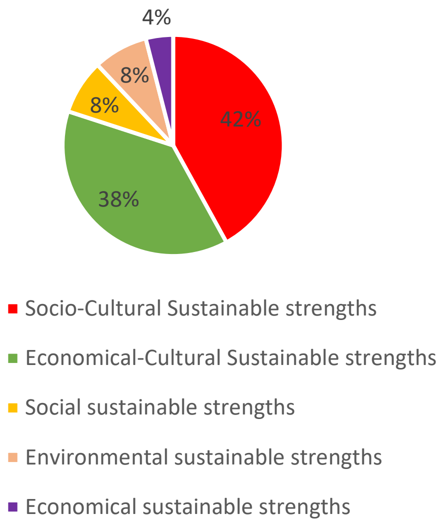

Figure 9: Classified major sustainable Strengths in AFM (Source: Researcher).

According to the analysis in **BFM**, major strengths in socially sustainable measures are publically accessible waterways, publically accessible streets, and Well-connected inland ways. Major strengths in Socio-cultural strengths are Naturally preserving traditional agricultural areas, Preserve traditional riverside architecture, certifying homestay accommodation, Performing arts for kids and programs for sharing local knowledge, Maintaining the floating market as a regional asset, allowing only local people as vendors and hawkers, health learning places like the traditional Thai medical center, The community gains self-pride, awareness, and wisdom regarding the conservation of natural resources and local history, Increase the quality of life of senior citizens. Create a place that reinforces health tourism for aging people; the local community forms a network of a market committee for its development, Availability of skilled entire workforce, Recreation activities like homestays, platforms for garden activities, agricultural occupation since the *Ayudhaya* period, especially gardening, e.g., fruit gardens and flower gardens, Builds good family relationships due to the availability of communal spaces, Performing cultural traditions, Fairs and celebrations in *Thai* culture every month, Use of the riverside agricultural community's culture as a tourist development and Friendly and caring staff, Once a waterfront market again into a market. A significant strength in Economic sustainability measures is that A maximum of five stalls can have the same type. Major strengths in Economical-cultural sustainable measures are that Outside vendors are deprived of accessibility; Inhabitants are employed at the market; villagers find their extra income from the market, presence of local arts and crafts, Diversity of culinary arts, local farms, and way of life to be explored by tourists, Local Souvenirs and handicrafts. A major strength in Environmental sustainability measures is Outdoor eating combined with Si *Nakhon Kheun Khan Park*, a vast botanical garden with a large lake and bird-watching tower.

According to the above results, the following chart was prepared, indicating that **62% are socio- Cultural sustainable strengths, 21% are Economic-Cultural sustainable strengths, 10% are socially sustainable strengths, and 3% are Environmental and Economic sustainable strengths; thus, 83% of the major strengths are culture impacted strengths.**

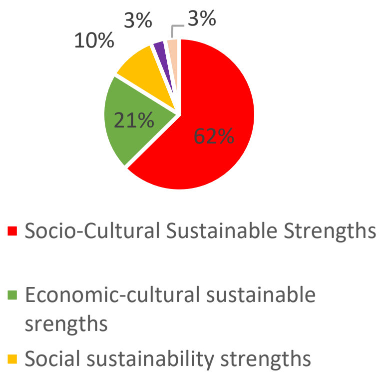

Figure 10: Classified major sustainable Strengths in BFM (Source: Researcher).

4.3 Analysis of Major weaknesses in the major case study: FMP

According to the analysis in **FMP**, major weaknesses in Socio-Cultural sustainability measures are the absence of community-oriented lands, the market not connected to any other tourist destination in *Pettah,* Absence of provisions for the city's educational sector as a public space. Lack of a specified local community that can nourish the market, Market has no provisions for disabled access therefore not inclusive to everybody, No variety of activities for tourist potential like food festivals, fairs, boat tours, floating restaurants, etc., Once industrialized land has turned into a tourism cum commercial land, Lack of community spaces, Lack of community engagement activities, Majority of the vendor's community are not satisfied with the location decision, No cultural traditions are practiced, No cultural fairs or festivals are held, No cultural rejuvenating project is revived, Over bloom of algae causing visual pollution in the canal, Lack of city tours via water and Lack of unique traditional buildings of the riverside community. Major weaknesses in Economic-Cultural sustainability measures are No strategies to trickle down local poor via the market, The market does not help to city's economic growth, Vendors are from different areas of Sri Lanka, and No variety of local products (local arts and crafts, local food dishes which are important parts of culture for tourism). Major weaknesses in Environmental sustainability measures are the environment is less maintained and polluted and air is polluted due to the polluted water in the canal.

According to the above results, the following chart was prepared, indicating that **74% are Cultural weaknesses, 13% are Economic-Cultural weaknesses, 9% are weaknesses, and 4% are Social weaknesses; thus, 87% of the major weaknesses are due to lack of culture-impacted.**

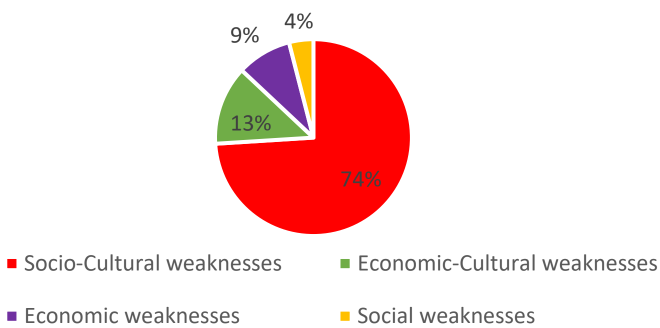

Figure 11: Classified major weaknesses in FMP (Source: Researcher).

The lack of a cultural role in the FMP weakens it, while minor case studies in Thailand show that the role of culture strengthens it. Thailand's floating markets have thrived due to their cultural adaptation to seasonal flooding and the use of inland water canals for travel and transportation over decades. However, in the case of FMP, communities like commuters, retailers, and vendors have no cultural ties to the canal or lake, making the implementation unsustainable. Additionally, the FMP does not depict anything distinctive to the local culture, making it unsuitable for tourism without a distinctive cultural element.

5. Conclusion

The research findings prove that the FMP is unsustainable because of the lack of a cultural role, whereas the minor case studies in Thailand are sustainable with their role of culture. Hence, the hypothesis is proven that the lack of a city's cultural role in urban development leads to its non-sustainability. The findings also answer the research question: "Is the floating market in ***Pettah*** unsustainable because it does not play the role of local culture?"**Yes, It is.**

5.1 Contribution of the Research Findings about Existing Published Work

The research findings would nourish the research model presented by *Glen Hole* (2020) with new culture-related measures with the measures presented for the mere social, economic, and environmental pillars of sustainability presented by *Denis Michalina, Peter Mederly, Hans Diefenbacher,* and *Benjamin Held* (2021), and the research findings would provide necessary actions to take before implementing urban developments for sustainable built environments.

Author Contributions

This paper was extracted from my dissertation submitted in partial requirement for the degree of Bachelor of Architecture of General Sir John Kotelawela Defence University, Southern Campus, Sri Lanka, accomplished by R.T.L.S. Rajapakshe (1) in 2022. N.L. Rubasin Gamage (2), a senior lecturer at General Sir John Kotelawela Defence University, Southern Campus, and H.P. Munasinghe(3) the associate professor of the General Sir John Kotelawela Defence University, Southern Campus, were the supervisors of the research, and all authors, approved the final manuscript.

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MACHINE LEARNING APPROACH FOR MODELING MODE CHOICE DECISIONS OF SRI LANKAN TRAVELLERS

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Abstract: Analysing travelers' mode choices is an important task to get insight into transportation planning, policymaking, and understanding future travel demands and travel mode choices. Travel mode choices are primarily estimated by using discrete choice models. Among them, the Multinomial Logit model (MNL) can be indicated as the most widely used mode choice model. Machine Learning (ML) is an emerging approach that can also be used for modeling mode choices. In contrast to MNL models ML models do not make drastic assumptions about the data set. Therefore, the ML approach has some advantages for modeling the mode choice over the traditional MNL approach. This study is set to look at a possible ML approach, specifically the Support Vector Machine (SVM) algorithm, for predicting travelers' mode choices using trip-specific, socioeconomic, and household data. Raw data was gathered by conducting an online and a face-to-face questionnaire. The study evaluates the performance of the SVM algorithm under different kernels and criteria, including prediction accuracy, precision, recall, and also F1 score which is used to measure the harmonic mean of precision and recall. The latter part of the study compares the MNL approach and the ML approach, where the former considers nine modes with travel time, cost, and distance as parameters estimated using utility maximization theory. The ML model is presented as an alternative solution for predicting mode choice, addressing the limitations of traditional models.

Keywords: Machine Learning; Multinomial Logit Model; Support Vector Machine; Travel Mode Choice; Transportation Planning

1. Introduction

Understanding the choice of travel mode is important as it affects the efficiency of travel, the space required for transportation functions, and the range of mode alternatives available for users. Different factors affect travel mode choice modeling including trip-specific data, socio-economic data, and household data associated with each trip. Thus, the Multinomial Logit (MNL) model can be indicated as the most widely used mode choice model for the discrete mode choice models (McFadden, 1973).

Conversely, Machine Learning (ML) is used to define an algorithm that builds models through a methodical pattern in statistically significant data. The usefulness of ML models has already been demonstrated in different areas of the transportation sector. Due to ML algorithms not making strong assumptions about the studied data, they can represent complex relationships of data in a non-linear, general, and data-based way (Bishop, 2006). Therefore, ML models come across as the better model for modeling travel mode choices.

This research aims to estimate travellers' mode choice parameters, by using ML algorithms and compare them with the MNL approach. There are two specific objectives of this study;

- To develop a method to estimate mode choice parameters by using the Support Vector Machine (SVM) and Random Forest (RF) method.
- To perform a comparative study of parameter estimation between ML and MNL approaches.

The study focused on trips related to the whole country. It was considered only the travel mode behavior of participants aged 18 and over. Trip data were collected based on trip-specific data (travel mode, trip distance, cost, time, etc.) socio-economic data (gender, age, ethnicity), and household data (income, number of cars/ bicycles, etc.). All trip purposes were considered, which included work, education, leisure, shopping, etc.

The remainder of the paper is organized as follows. In Section 2, it is included the literature as survey-related contributions on modeling techniques, survey methods, and result interpretation. Following that, the design principles are defined in Section 3 as the methodology, which provides a foundation for the proposed work, then it also discusses a method for basic feature extraction methodology for a genuine data set. Based on this methodology, the development of an ML-based algorithm and MNL-based algorithm is presented in Section 4 under the results and discussion. Finally, Section 5 concludes the paper and outlines the future work.

2. Literature Review

Models of travel mode choice have been traditionally estimated using a discrete choice framework while the most used discrete model is MNL. It is based on the utility maximization theory and has a mathematical structure that is required for parameter estimation. Therefore this model is widely used in transportation research. The negative impact of the MNL model is that they assume that the probabilities of each pair of alternatives are independent of the presence or characteristics of all other alternatives (McFadden, 1973). As a result of that, the introduction of any alternative has the same proportional impact on the probability of each other alternative. Violation of this assumption yields inconsistent parameter estimates and biased predictions. Therefore, parameter estimation is more difficult for the MNL model (Hagenauer & Helbich, 2017).

2.1 Modelling Techniques

Omrani, 2015 studied four ML methods (Artificial Neural Network Multilayer Perceptron (ANN-MLP), Artificial Neural Network Radial Basis Function (ANN-RBF), multinomial logistic regression, and SVM) that were used to predict the travel mode of households. Ali, et al., 2021 evaluated the efficacy of Neural Network (NN), RF, Decision Tree (DT), and SVM, ML models against a logistic regression in predicting travel mode choice. In addition, ML models were compared with Binary logistic regression and used to predict travel mode choice. Jaramillo & Juan, 2019 studied ANNs, DTs, and SVM models that were used for modeling travel mode choice. The SVM model was compared with several models such as NNs, Extreme Gradient Boosting (XGB), Bayesian Networks, and the Standard SVM model (Qian, et al., 2021). The performance of those models has been evaluated by accuracy, precision, recall, and F1 score criteria. Hagenauer & Helbich, 2017 compared the predictive performance of the MNL and the six ML classifiers (Naïve Bayes (NB), SVM, ANN, BOOST, BAG, RF) for travel mode choice analysis.

Zhao, et al., 2020 carried out a study to examine the basic differences in model development, evaluation, and behavioral interpretation between logit models and seven machine learning models for mode choice modeling. A study, by Salas, et al., 2021 compared the predictive performance of five machine learning classifiers (K-Nearest Neighbours (KNN), NN, RF, SVM, XGB) and MNL and MMNL models.

2.2 Survey Methods

User's travel mode choice in Malaysia was studied by Ali, et al., 2021 using the data collected through the Revealed and Stated Preference (RPSP) surveying technique. Omrani, 2015 suggested the use of NN outer to predict travel mode choice based on the Socio-economic Panel Survey Liewen Zu Le iceberg (PSELL Survey). Richards & Zill, 2019 used the Victorian Integrated Survey of Travel and Activity (VISTA), while Qian et al., 2021 analyzed the 2017 National Household Travel Survey (NHTS) - California dataset for imbalanced mode choice data. Sekhar et al., 2006 collected travel behavior data through a traditional home-based personal interview survey, while Hagenauer & Helbich, 2017 used data from the Dutch National Travel Survey (NTS) conducted from 2010 to 2012 for their study. Wang & Ross (2018) conducted a case study to collect trip data from Delaware Valley Regional Planning Commission, while Chang et al., 2019 collected travel diary survey data from the Mobi Drive project. Zhao et al., 2020 used data from a stated-preference survey completed by faculty, staff, and students at the University of Michigan, and Salas et al., 2021 used a synthetic dataset to assess model accuracy and investigate variable importance through a permutation-based method.

2.3 Result Interpretation

Ali, et al., 2021 showed that the NN model has a higher accuracy than the Binary Logistic regression model. Omrani, 2015 also, confirmed that the NN model was the best when compared to other ML models (Multinomial logistic regression and SVM). Jaramillo & Juan, 2019 pointed out the RF and DTs algorithms in the ML model as the best way to model travel mode choice.

The Random Forest Decision Tree (RFDT) model had high accuracy due to tree-structured classifiers, as shown by Sekhar, et al., 2016. Hagenauer & Helbich, 2017 found RF produces the most accurate predictions. The XGB model has higher accuracy than the MNL model (Wang & Ross, 2018).

3. Methodology

3.1 Overview

As per our understanding, no one has done a study to develop a method to estimate mode choice parameters by using the ML approach based on data collected in Sri Lanka. The flow chart illustrated in Figure 1 describes the basic steps involved in the methodology.

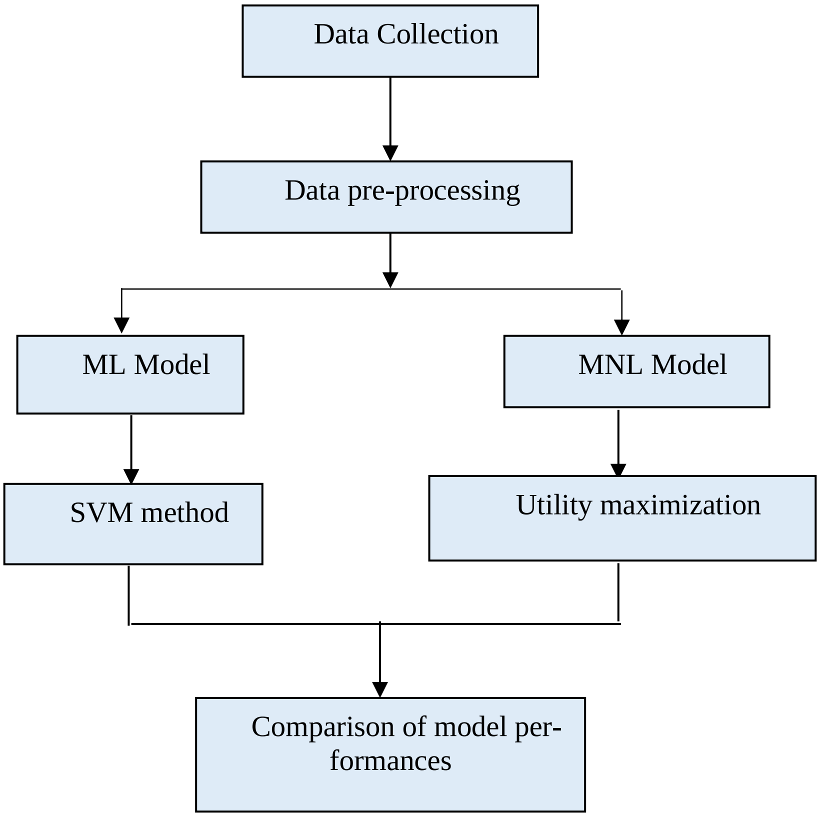

Figure 1: Flow chart of methodology.

3.2 Data Collection
Raw data were obtained from an online survey and a face-to-face questionnaire survey to identify the mode of transport used. It was focused on trips of the entire country to detect methodical patterns in travel behavior data. For this study, 1500 raw data were collected which agreed with all set conditions.

3.3 Data Preprocessing
Data pre-processing refers to the technique of preparing (cleaning, formatting, and organizing) the raw data to make them suitable for building and training models. Refer to Figure 2 for the cross-sectional analysis of the raw data set and refer to Table 1 for a summary of the raw data set obtained from data collection. The value 0,1,2,3 stand for ‘Bus’, ‘Other vehicles’, ‘Train’, and ‘Private vehicles’ respectively.

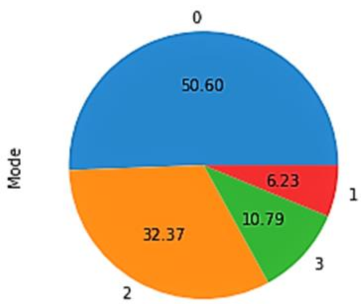

Figure 2: Cross-sectional analysis of the data set.

Table 1: Summary of the raw data set

Mode	Interpretation number	Count for each mode
Bus	0	544
Other vehicles	1	116
Train	2	348
Private vehicles	3	67

Due to the higher number of responses for 'Bus' and 'Train' the data set can be considered as an imbalanced dataset. A common, unwanted situation that results from such a dataset is that an ML algorithm could score with higher accuracy by always predicting biased to 'Bus' or 'Train'. Over-sampling of the minority classes could be introduced as a potential solution for learning from an imbalanced dataset to gain optimal classification results. The oversampling process starts by identifying the minority class in the dataset. Once identified, the technique randomly selects instances from the minority class and creates synthetic data points based on their characteristics. This process increases the number of samples in the minority class of an imbalanced dataset to improve the model's ability to learn from and generalize to the minority class. The minority classes of 'Other vehicles' and 'Private vehicles' were oversampled up to 544 responses. Figure 3 shows the cross-sectional analysis of the data set after oversampling.

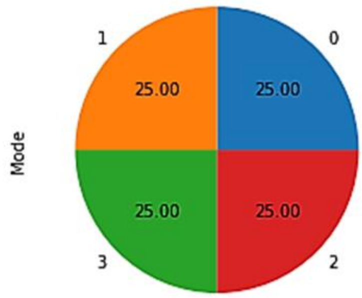

Figure 3: Cross-sectional analysis of data set after oversampling.

3.4 Analysis with ML model

This analysis was carried out using SVM algorithms. After pre-processing of data, all data referred to the SVM model with the hyperparameters as described below, and the outputs were obtained.

3.4.1 Cross Validation

A five-fold cross-validation technique was used to evaluate the performance of the data set. The data set was split into five different subsets. Then four subsets were used to train the data and the remaining subset as test data. Then the model was tested against each of the folds and then finalized the model. Finally, the model was tested against the test set.

3.4.2 Feature Selection

Here, the filter method was used as the feature selection technique. Under that, the data set ranked for each feature based on a univariate metric. Then the highest-ranking independent features with no constant variables, fewer quasi-constant variables, no duplicate rows, high correlation with the target variable, and low correlation with other independent variables.

3.4.3 Support Vector Machine Algorithm

The goal of the SVM algorithm is to create the best line or decision boundary that can segregate n-dimensional space into classes. SVM can be of two types. They are the linear SVM model and the non-linear SVM model. Under linear SVM there is only the linear kernel function and under non-linear SVM there are polynomial kernels, radial basis function kernels, and sigmoid kernels.

3.4.4 Model Performances

This study used four evaluation criteria to evaluate the performance of the developed model. These criteria included prediction accuracy, precision, recall, and F1 score which is used to measure the harmonic mean of precision and recall. Furthermore, these four criteria are based on the terminology of the confusion matrix.
The terminology implemented in the confusion matrix can be explained as shown in Table 2.

Table 2: Terminology used in the confusion matrix.

		Predicted	
		N	*P*
Actual	*N*	TN	FP
	P	FN	TP

where, TP: True Positive, these are cases predicted as yes. TN: True Negative, the cases are predicted as no. FP: False Positive, the cases are predicted as yes but users will choose the actual one. FN: False Negative, the cases are predicted as no but users will not choose the actual one.

Formulas for four evaluation criteria are shown in Eq. 1, Eq. 2, Eq.3, and Eq.4

$$Prediction\ Accuracy\ = \frac{(TP + TN)}{(TP + TN + FP + FN)\ \times\ 100} \tag{1}$$

$$Precision\ = \frac{TP}{(TP + FP)} \tag{2}$$

$$Recall\ = \frac{TP}{(TP + FN)} \tag{3}$$

$$F1 - score = 2 * \frac{Precision\ *\ Recall}{Precision\ +\ Recall} \tag{4}$$

3.5 Analysis with MNL model

The parameters for the utility function were defined by using R-studio software.

The general formula for the utility function shown in Eq. 5

$$U = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \cdots\ \beta_n x_n + \xi \tag{5}$$

Here ;

$x_1,\ x_2, \ldots x_n$ are attributes
$\beta_0, \beta_1, \ldots . \beta_n$ are parameters
ξ is the random error term

The same data set that was used for the SVM model is employed with MNL for the benchmarking. However, the MNL model is analyzed based on the likelihood of commuters selecting travel modes. Nine available modes were considered in our study. They are bus, car, train, van/jeep, motorbike, three-wheeler, taxi, bicycle, and walking.

Initially, it was identified what modes of travel are available to commuters for each trip using a data sample. Then, if any mode is available for each trip, the available distance, available travel time, and available travel cost of each mode are considered. Thus, the data sample was rearranged according to the above three variables concerning the modes for each trip.

By using the MNL model results were taken for initial likelihood, Maximum likelihood, Rho-square, Corrected rho-square, Parameter estimates, and t-statistic values.

4. Result and Discussion

4.1 ML Model

Table 3 shows the results from each kernel function under the SVM model analysis.

Table 3: Results from each kernel function

		Confusion Matrix				Precision	Recall	F1-Score	Accuracy
		0	*1*	*2*	*3*				
Polynomial Kernel	*0*	27	36	18	22	0.44	0.46	0.45	0.48
	1	4	89	10	9	0.67	0.57	0.61	
	2	17	26	52	18	0.62	0.55	0.60	
	3	15	22	17	54	0.65	0.56	0.60	
Radial Basis Function Kernel	*0*	27	36	18	22	0.43	0.26	0.33	0.61
	1	4	89	10	9	0.51	0.79	0.62	
	2	17	26	52	18	0.54	0.46	0.50	
	3	15	22	17	54	0.52	0.50	0.51	
Sigmoid Kernel	*0*	43	42	7	11	0.23	0.42	0.30	0.25
	1	47	45	17	3	0.25	0.40	0.31	
	2	39	48	22	4	0.45	0.19	0.27	
	3	56	47	3	2	0.10	0.02	0.03	
Linear Kernel	*0*	48	21	16	18	0.35	0.47	0.40	0.38
	1	30	37	28	17	0.36	0.33	0.35	
	2	24	20	53	16	0.46	0.47	0.46	
	3	37	24	19	28	0.35	0.26	0.30	

4.1.1 Comparison among kernel functions

The values on the diagonal of the confusion matrix represented true positive values associated with each mode. Furthermore, Precision, recall, and F1-score were obtained for each mode under different kernel functions. Prediction accuracy was taken for the each of kernel functions.

In polynomial kernel 'Other vehicle ' has the highest precision, recall, and F1 score value. Then the radial basis function kernel 'Train' has the highest precision but 'Other vehicle' has the highest recall and F1 score value. For the sigmoid kernel 'Train' has the highest precision, 'Bus' has the highest recall, and 'Other vehicle' has the highest F1 score value. Finally for linear kernel 'Train' has the highest precision and F1 score value and 'Bus' and 'Train' have the highest recall value. When comparing each kernel function radial basis function kernel has the highest F1 score value. When comparing the accuracy value for all kernel functions, the radial basis function has the maximum prediction accuracy of 0.61.

4.1.2 Discussion for ML model

Precision measures the proportion of true positive predictions made by the model. It is a useful metric for evaluating the model's ability to avoid false positives. Recall measures the proportion of true positive cases that were correctly predicted by the model. It is a useful metric for evaluating the model's ability to avoid false negatives. To balance precision and recall, It is often used the F1 score, which is a combination of the two metrics. The F1 score is calculated as the harmonic mean of precision and recall, and it provides a balance between the two metrics.

According to that 'other vehicles' in the radial basis function has the highest F1 score value. The harmonic mean between precision and recall (F1 score) tends to be closer to the smaller number in a pair. Thus, the F1 score will only be high if both precision and recall are high, ensuring a good balance of both. Also when comparing the accuracy of 4 kernel functions, the radial basis function kernel has the highest accuracy value of 0.61.

4.2 MNL Model

Table 4.2 shows the parameter estimation results by using the MNL model.

Table 4.2 Parameter estimation results

Parameter	Result
Estimated parameter of travel time	-0.9039
Estimated parameter of travel cost	-0.0035
Estimated parameter of travel distance	-0.4266
t-statistic value of travel time	-8.5328
t-statistic value of travel cost	-2.8941
t-statistic value of travel distance	-5.6044
Initial likelihood	-1114.47
Final likelihood	-958.87
Rho-square (likelihood ratio index)	0.1396
Adjusted rho-Square (Adjusted likelihood ratio index)	0.1315

The likelihood ratio index and adjusted likelihood ratio index values of 0.1396 and 0.1315, respectively. The initial likelihood ratio of -1114.47 represents the likelihood of the null model, while the final likelihood ratio of -958.87 represents the likelihood of the estimated MNL model.

4.2.1 Discussion for MNL

By using the utility function the estimated parameter of travel time, the estimated parameter of travel cost, and the estimated parameter of travel distance were obtained as negative values. That means travel time, travel cost, and travel distance are negatively proportional to the utility of a travel mode. Among these three values, the highest negative value (-0.9039) has been taken by the estimated parameter of travel time. Therefore travel time has the highest significant contribution to the utility function in choosing the mode for each trip.

Initial likelihood, maximum likelihood, rho-square, corrected rho-square, t-statistics, and parameter estimates of alternative values were taken under the MNL model. According to the obtained likelihood ratio index and adjusted likelihood ratio index values, the MNL model was a good fit for the observed data.

5. Conclusion

According to the discussions obtained for the ML model and MNL model, the following conclusions can be made. Among all of the kernel functions of the SVM model, the radial basis function kernel estimates the correct mode choice method more accurately than other kernel functions. As shown in the above discussion for the MNL model travel time has a significant contribution to the utility function in choosing the mode for each trip. In conclusion, though this research has been done, there exists a research gap regarding the comparison between mode choice modeling by using the ML method and MNL method in Sri Lanka. Therefore it is important to investigate mode choice modeling using other ML models and learning techniques and compare the result with the MNL model in future work.

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URBAN GOVERNANCE AND POLICY FORMULATION IN URBAN SLUMS AND SHANTY DWELLERS IN SRI LANKA (SPECIAL REFERENCE TO THE 'HAVELOCK' SLUMS IN COLOMBO DISTRICT)

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Abstract: The resettlement and management of slums and shanty dwellers has become a popular discourse that is influencing sustainable urban management around the world. Sri Lanka has implemented various public policies as urban governance approaches in this regard. After the 30 Years' War, numerous programs were implemented by ruling regimes focusing on the people of the capital city, Colombo. In this context, it is expected to study through this research the failure of the urban governance and public policy formulation process in the management and resettlement of slums and shanty dwellers. The objectives of the research are to describe the urban governance approaches related to slum and shanty construction and the resettlement process and also to find out the relationship between the resettlement process and the policy-making process. In addition to finding out the new norms and changes in public policy and public administration in the resettlement of slum and shanty dwellers. The main research sample is based on 130 from 'Havelock' slums and shanty dwellers (18-70) of the age category. The primary data were collected through questionaries, interviews, and participatory observations while secondary data were collected through academic journals, research articles, and relevant reports. Maslow's theory, Neoliberalism theory, patron-client relationship, and theory of space production were utilized for theoretical background. The SPSS software was used to analyze the quantitative data and the collected qualitative data were analyzed by the thematic analysis method. The research findings explain that a patron-client relationship is maintained in the introduced public policies and urban governance process. This relationship is also connected with the bureaucracy. Moreover, some slums and shanty dwellers strongly express their opinion opposed to resettlement. The urban space is the social space for the dwellers as their identity, culture, and sense of belonging are bounded by their location. In contrast, the policymakers view urban space as an abstract sphere that can be used in economic development. It can be concluded that political relations and bureaucratic features are operating in the urban governance programs and public policy formulation process that are continuously implemented for the slum and shanty dwellers. This has excluded the underserved communities from their right to the city.

Keywords: Patron-Client Relationship; Poverty; Public Policy; Shanty Dwellers; Slums; Urban Governance

1. Introduction

Current global situation the foci of poverty are shifting to cities. This is a situation which is aggravated by the serious economic crisis. One of the most obvious signs of this process is the formation of slums and shanty towns, whose inhabitants are surviving amidst poverty and neglect (United Nations, 2006). The process of resettlement of people in slums and shanty dwellers is a problem directly related to policy formulation and sustainable development. Social, economic, and environmental changes and policies can be identified behind that problematic situation.

Since British rule, various governments have utilized a diverse range of strategies and policy formulations the regulate the spread of slums and shanty dwellers in the city of Colombo. In the development discourse of Sri Lanka after the war, several policy programs were implemented through the urban governance process in the determination to make the city of Colombo a beautiful area. Under the purview of the Urban Development Authority (UDA), the URP planned to relocate nearly 70,000 to 135,000 families (between 280,000 and 500,000 people) into "modern" high-rises (Perera et al., 2014).

As reported by, GOSL (Government of Sri Lanka) poor land use patterns, growing slums and shanties, poor infrastructure, poor solid waste management, and weaknesses in municipal administration are key obstacles to achieving the development dream (Rasnayaka, 2019). Consistently, the construction of urban slums and shanty dwellers as well as the resettlement process of these shanty-dwelling people can be identified as a major problem in Sri Lanka especially in the Colombo district. It is also clear that this crisis is directly linked to the urban governance and policy formulation process.

2. Research Problem

The research problem that is expected to be studied through the research is, "Why do the urban governance and policy formulation process fail to successfully resettle the urban slum and shanty dwellers?"

2.1 Research Objectives

RO 01 – To describe the urban governance approaches related to slums and shanty construction and the resettlement process.
RO 02 – To find out the relationship between the resettlement process and the policy formulation process.
RO 03 – To find out the new norms and changes in public policy and administration in the re-settlement of slum and shanty dwellers

2.2 Research Questions

RQ 01 - How are urban governance approaches related to the slum and shanty construction and resettlement process?
RQ 02 - What is the relationship between the resettlement process and the policy formulation process?
RQ 03 - What are the new norms and changes in public policy and public administration in the resettlement of slum and shanty dwellers?

2.3 Conceptual Framework

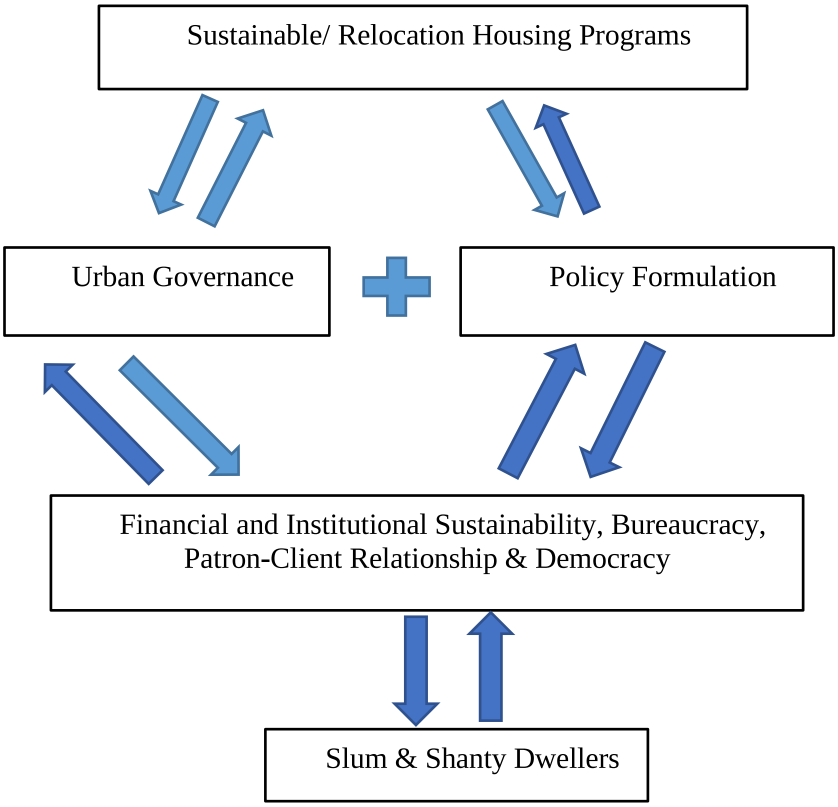

Figure 01: Conceptual Framework; by Authors, 2023.

3. Methods & Methodology

3.1 Population, Sample & Sampling Techniques

The ‘Havelock’ slums and shanty houses system was used as the research field and the research sample consists of 130 respondents, representing each criterion for successful study. In addition, 25 bureaucratic from the Ministry of Urban Development and Colombo Municipal Council and 05 members of non-governmental organizations were selected for the sample. Accordingly, the total sample population comprised 160 respondents.

3.2 Data Collection Methods

The mixed method which has amalgamated both quantitative and qualitative perceptions was used for the current study. Accordingly, questionaries, in-depth interviews, and non-participatory observation were conducted as primary data collection methods. The secondary data for the study were gathered mainly through academic research publications such as case studies, books, and journal articles. Furthermore, both government and nongovernmental organizational reports which are specifically focused on the informal settlement were also referred.

3.3 Theoretical Framework

Patron-client Relationship Theory (means the selective favorable treatment of individuals by the state, usually in exchange for votes for the politician or the party offering the selective treatment; Klopp, 2012); Maslow’s Human Needs Theory (Maslow's hierarchy of needs is a motivational theory in psychology comprising a five-tier model of human needs, often depicted as hierarchical levels within a pyramid; Saul McLeod, 2018); Elite Theory and Policy Cycle (The policy cycle framework originates from the idea of organizing and ordering the complexity of policy-making; Lasswell 1956) were majorly utilized for the current study.

Furthermore, the 'Theory of Space Production' which was introduced by a radical urban sociologist Henri Lefebvre was used to strengthen the analysis. Lefebvre's concept of 'right to the city' was applied following the above theory. The abolition of the rights of the population who are residing in underserved settlements in Sri Lanka is directly related to the said theoretical and conceptual analysis.

4. Findings and Discussion

4.1 Relationship of urban governance approaches with Slums and Shanty Dwellers in the resettlement process

The emerging discourse on urban governance has become a very popular topic in recent times, with discussions on the policy cycle, sustainable cities, and democracy. Globally, rapid urbanization has caused many issues in cities. Urban sprawl, the urbanization of poverty, higher unemployment, housing affordability, shortage of infrastructure investment, weak financial capacity, poor urban governance, urban inequality and gender inequality, crime and human insecurity, and environmental impacts are some of these issues (Zhang, 2015, pp. 11–22).

Attempts were made on several occasions to implement projects covering the "Havelock" (Isuru Place and Swarana Mawatha) zones to resettle the slum and shanty-dwelling people in the hope of adapting the city of Colombo to sustainable development objectives. After 2015, the Havelock area was also focused on the implementation program of 33 housing projects related to the resettlement process of slum and slum people in Colombo-North and Colombo-South. As Colombo is an area centered around the urban population, the dialogue built with the people belonging to the project is extremely important in the implementation of urban governance approaches. The following chart shows the nature of the awareness of the communities who were subjected to relocation through the said government projects.

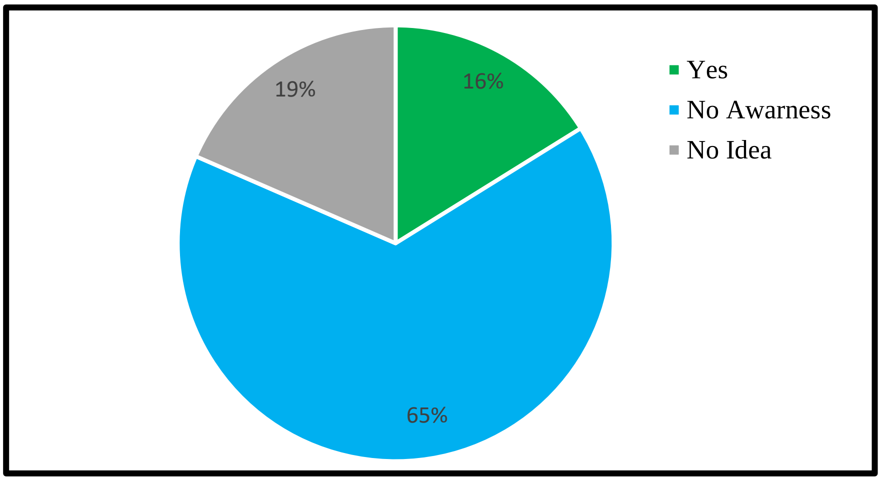

Figure 02: The Nature of the Awareness of the Resettlement Projects, Survey, 2023.

As per the guidelines for planned relocation by the UNHCR, 'relocated persons and other affected persons should be informed, consulted, and enabled to participate in decisions on whether, when, where, and how a planned relocation is to occur, as appropriate' (UNHCR, 2015: 11). However, as per the responses of the community, majority (65%) had no prior understanding of the projects being introduced for the people and it was also possible to identify people who had no idea about it. This shows the less community-sensitive nature of the government policy formulation. This can be further discussed through the actors of awareness that they were dealt with.

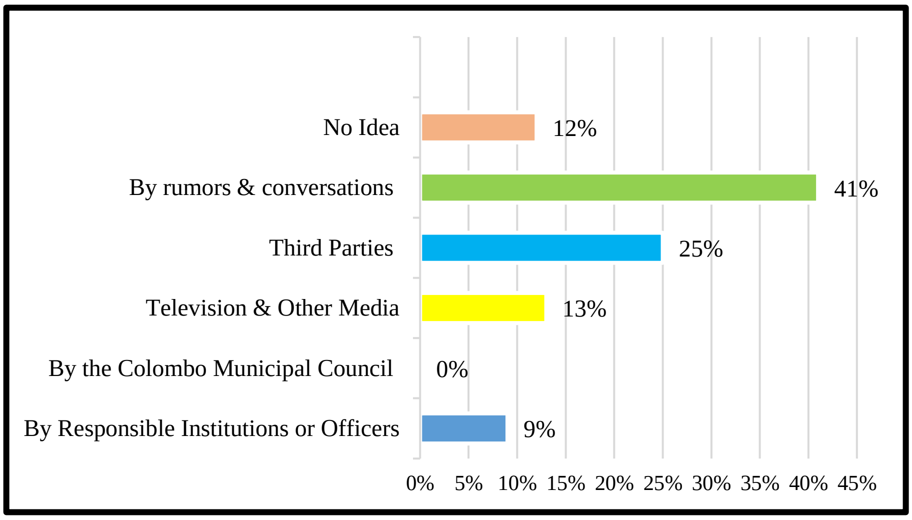

Figure 03: Nature of the Projects Awareness, Survey, 2023.

Analyzing the above data, neither the Central Government nor the Colombo Municipal Council has failed to provide prior understanding to the people. Almost a majority of the entire sample gained knowledge through rumors or conversations that took place among themselves. Urban governance approaches in Sri Lanka's resettlement process are called urban regeneration programs (Annexures I and II). Amir Tahmasebi et al. (2016) point out that in every city there are underused and underutilized lands which weakens the image, liveability, and productivity of the city, and urban regeneration policies usually target these declining or vacant land parcels. Thus, the term urban regeneration in development discourse means making maximum utilization of the unused, unproductive lands of a city.

Accordingly, in the democratic discourse, the process of providing a sustainable city and a more satisfying life to the slum and shanty-dwelling people is done away from the concepts of urban governance, Participatory, and Local Democracy, as well as Sustainable Development. About the selected research field, there is an inverse or different relationship between the resettlement process and the variables of urban governance approaches and sustainable cities.

4.2 Relationship between the Resettlement Process and the Policy Formulation Process in Colombo District, Sri Lanka

Public policy is an institutionalized proposal or a decided set of elements like laws, regulations, guidelines, and actions to solve or address relevant and real-world problems, guided by a conception (Lassance, 2020; Martinez, 2022). The result of a policy should be the welfare of the people. According to responder 01's ideas[1], an official of the Colombo Municipal Council believed the two concepts of a sustainable city and regeneration are the basic criteria of the policies, but he had no understanding of the steps of the policy cycle. The active participation of the people in the process of making such policies or programs successful, as well as the functioning of an official government, is very important to limit the electoral politics that are controlled and maintained through policies. However, the ideologies and opinions held by the people of the field were opposite in nature. Their basic idea was that various programs or projects are brought for political needs and the main aim is to remove themselves from this area. This can be analyzed more clearly through the following graph.

[1] *"It was decided to provide housing facilities through the 2016 project with the aim of providing a more sustainable city and a satisfying life to the slum dwellers in this area. The first phase was to provide temporary residences and build the housing project in this area and settle them there*."- In an interview with a 45-year-old civil servant working in the planning and project department of the Urban Development Authority.

Table 01: Ideas of the research sample on the resettlement policies and projects, Sample Survey, 2023

Nature of the idea	**Number of responses**
To improve the quality of life	11%
Political Interests	26%
Electoral Politics	31%
Personal Interests (Business)	19%
No Idea	13%

Most of the respondents think that such policies or projects are simply implemented for electoral politics or political interests. According to Maslow's theory of needs, a secure habitat is essential for a satisfied life. But what happens in practice is that those basic needs are politicized in different ways. In the research, it was revealed that the politics of slums and shanty dwellers are also working as a part of the electoral politics.

Merrifield (2014) points out how the state has managed to exclude political engagements from urban matters: The reason may be obvious in our age of "experts" and "technocrats", in this era some describe as "post-political"; positivism has always hidden behind the shield of quantification. and "objectivity", always tried to rid itself of politics. In that sense, positivism/empiricism is a convenient methodology for technocrats trying to find consensus without conflict. (p. 3) To elaborate on Merrifield's idea, the discussion should be directed to the positivist stance of the government in decision-making. Current policy decisions are always supported by generalities based on statistical calculations. The decisions are made based on empirical facts which are easily quantifiable and objectified. Accordingly, it is revealed that the policy-making process is working negatively in terms of resettling the slum and shanty-dwelling people by electoral politics. In other words, government policies and bureaucracy have been politicized by party and electoral politics.

Further, the policymaking has omitted what the community feels and needs before planning the resettlement. According to Henri Lefebvre (1996), the city is a social space for their settlers where their social bonds, everyday needs, livelihoods, cultural needs, and overall identity are bounded. However, he highlights that the policymakers do not usually tend to see the city in that sense as they are keen on using urban space for economic development. Accordingly, the policymakers who are governed by neoliberal ideologies see the slum and shanty areas as a waste of land that can be used for investments. Most of the resettlement policies are formulated in a way that fits with the above ideology. Therefore, most of the policies aren't compatible with the community's needs and apparently, they are abolishing the sense of belonging that the community has to their location. This has been always politicized and governed by electoral politics. Through that, slums and shanty dwellers are used as symbols of electoral politics, and it can be concluded that the necessary context is built through public policies and public administration.

4.3 Patron-Client Relationship between Urban Governance, Public Policy, and the Resettlement of Slum and Shanty Dwellers

It is also important to study the responses of urban governance and public policies to patron-client relationships in the resettlement process of slum and shanty dwellers. This process is directly related to the concept of the 'right to the city' Lefebvre (Lefebvre, 1996). Since a policy formulated by a government is implemented through public administration strategies, the resettlement process of slums and shanty dwellers should also be done according to those conditions. However, in practice, the field revealed that these policies or programs are maintained in a patron-client relationship.

According to the responder's II[2] & III[3] ideas; two main ways in which this patron-client relationship is formed can be identified. that is, 1. Between the Politicians and the People (Voters) 2. Between Politicians and Government Officers. The roles of patrons and clients that emerge between politicians and voters are based on poverty, welfare, and needs. The research revealed that 'slums and shanties' are used as an identity to attract the people living in these estates as voters. They are using the field for their political survival by giving temporary benefits to the people living in the 'Watta' and attracting them to their political ideologies. Through this, they do not need to build a more sustainable life apart from satisfying their daily needs. It is therefore obvious that policies or programs intended to be implemented are not practicable subject to a patron-client relationship. The research revealed that a patron-client relationship is maintained between politicians and government officials. The political ideologies maintained in this area have also influenced government officials in the resettlement of the slums and shanty dwellers. The public service has also been politicized due to the political system in place in Sri Lanka. Woodrow Wilson comments that public administration should be separated from politics because of the need to maintain the independence of public administration.

Also, the inefficiency of the public service as well as decision-making weaknesses were a major problem in the research field. Urban governance approaches are most successful only by building a close relationship with the grassroots. Consistently, problems arise in the process of resettlement related to patron-client relationships and urban governance as well as government policies. Not only the basic needs of the people but also the conditions of participatory democracy, the right to live in a city, and active citizenship are being politicized in the field.

5. Conclusion

The process of slum and slum resettlement is a social, political, and economic context that can be examined through several different approaches. Therefore, through this research, the relationship and problems between urban governance and government policies with the resettlement process of slum and shanty dwellers were discussed. Accordingly, the resettlement process of the slum and slum dwellers in Sri Lanka is a process that takes place through the leadership of the Urban Development Authority representing the Colombo Municipal Council and the Central Government. Even though numerous government policies and programs have been introduced for that purpose, many problems must be faced in attracting people to the process. In Sri Lanka's tier-shifting political system, electoral politics control the state policies and urban governance process, and the area is used as a symbol in politics. Slum and shanty politics are utilized for their election victory, and it is a factor that has a wide negative impact on the implementation of long-term plans or programs.

A sustainable way of life as well as the 'right to the city' is politicized through this. In democratic practice, policy-making and urban governance processes should be done according to the concepts of democracy. Nevertheless, in the field of research, the active citizen as well as participatory democracy is separated from that process. The consideration of urban space as an abstract space by the policymakers which is governed by the neo-liberal urban restructuring ideologies violates the rights of the communities who are residing in the underserved settlements while overlooking their relationship with their lands and communities. It can be suggested that government policies and urban governance approaches should be used in a well-managed manner to make the resettlement process of slum and shanty dwellers

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[2] Response II: "Once, the municipal council came and took details of a program to give us new houses. But we were not told from which side the houses will be received and how they will be received."- During the interview conducted with a 37-year-old woman in 'Swarnamavata

[3] Response III: "Once, the municipal council came and took details of a program to give us new houses. But we were not told from which side the houses will be received and how they will be received."

Response IV:6 "Most of the time, many people think that they are thinking of removing people by force. I don't know how that idea gets into people's heads. But in some programs, we also face problems."- In an interview with a 43-year-old civil servant working in the Colombo Municipal Council successful. There, politics should intervene in those processes for the maximum implementation of public welfare. For that, there should be a change in the political system in such a way as to minimize the patron-client relationship that operates through electoral politics, and public officials and the people should avoid politicizing their active citizenship. Through that, the urban management and government policymaking process will have the ability to establish a more sustainable life without the politics of slums or shantytowns, as well as the right to live in a city.

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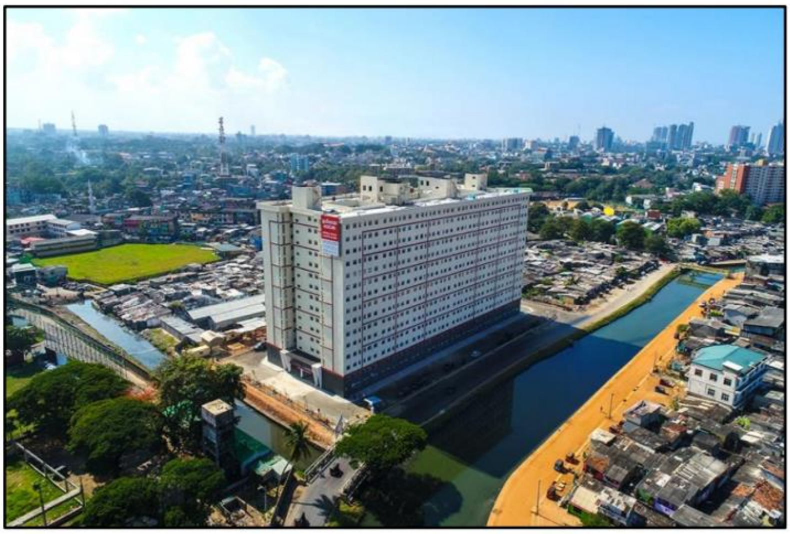
Annexure I – Havelock Town Slum & Shanties

Annexure II – Supposed Urban Regeneration Project



ICSBE 2023-299

GREEN IMPRESSIONS: UNDERSTANDING URBAN VEGETATION PERCEPTIONS IN UNESCO HERITAGE CITY KANDY

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Abstract: Urban areas play a crucial role in addressing sustainability concerns due to their significant ecological impact. Sri Lanka's "National Physical Planning Policy and the Plan-2017-2050" (NPPPP-2017-2050) emphasizes the importance of promoting a green built environment in urban development. In 2018, Kandy, a UNESCO World Heritage City celebrated for its historical, cultural, and environmental value, launched a street corridor tree-planting initiative. This study explores the nuanced perceptions of urban street corridor vegetation within this distinctive context. Nestled amidst hills on a plateau, Kandy faces the challenges of air pollution circulating within the city. To examine public opinions on urban vegetation, a comprehensive survey targeted two respondent groups: city residents and visitors, both local and foreign. Using observation and field surveys, this study revealed insights into perceptions and attitudes toward Kandy's street corridor vegetation. It identified 34 short and long vegetation belts in the city's grid areas. Foreign visitors were relatively scarce, while a significant proportion of respondents declared themselves as regular or occasional visitors, underscoring the city's enduring appeal. Regarding urban vegetation, 45.61% of respondents had a positive view and somewhat positive view, emphasizing its aesthetic appeal and benefits like fresh air and shelter. 5.26% were neutral, and 3.51% expressed a negative impression. Concerns encompassed potential harm to ancient monuments, damage to internal drainage and electrical systems, restricted pedestrian pathways, increased bird populations impacting historic buildings, and pavement damage caused by tree roots. The study uncovered diverse perspectives on enhancing urban greenery, particularly focusing on aesthetics, environment, and culture. Participants provided a range of ideas and recommendations for enhancing urban vegetation in specific street corridors. This research provides valuable insights for urban planners and policymakers interested in preserving Kandy's heritage and environment. Additional research and initiatives are needed to align urban vegetation development with the preferences of residents and visitors, promoting sustainability and heritage preservation.

Keywords: Urban Vegetation; Perceptions; UNESCO Heritage City; Sustainability; Kandy

1. Introduction

City planning has a rich and storied history, with a recurring emphasis on aesthetics and greenery. Across different civilizations, the concepts of the "park city" and the "garden city" have consistently guided urban planning. In the Western world, particularly the United States, aesthetics and vegetation have been pivotal in defining urban planning success. Historically, urban greenery in the Western context was limited to gardens until the 16th century, when European cities began expanding beyond fortified walls, giving rise to tree-lined avenues and groves to cater to the upper classes for leisure activities and festivities (Botkin, 1993).

The significance of green spaces in cities is evident worldwide, serving diverse purposes such as vegetation belts along urban road corridors, residential and park plantings, and foreground or distant scenery plantings. Greenery enhances the urban environment by reducing the need for air conditioning, improving air quality, dampening noise, and creating a sense of tranquility. Furthermore, vegetation contributes moisture through transpiration and fosters habitats for wildlife. These factors have long been associated with the beauty and health of a city (Carne, 1994).

Kandy is the seventh-most populated city in the country, with a population of 111,701 (the World Population Review estimates that 600,000 people visit the city daily). On Full Moon Poya days and other holidays, the number increases as people visit the Sri Dalada Maligawa and other places of interest. In July/August, during the perahera season, an estimated additional 200,000–500,000 people come into the city daily (Sunday Observer). The UNESCO-listed city of Kandy is located in the central highlands of Sri Lanka. Kandy holds a unique position as the heart of the country's rich cultural heritage and legacy, with UNESCO designating it for its outstanding universal value in 1988. Central to Kandy's cultural importance is the iconic Temple of the Tooth, also known as the "Sri Dalada Maligawa," which houses the priceless relic of Lord Buddha's tooth. This sacred temple serves as a major attraction for tourists and pilgrims from around the world, drawn not only to its spiritual significance but also to its magnificent architectural and aesthetic appeal.

Kandy's climatic characteristics are notable, with abundant rainfall and a moderate temperature regime influenced by its elevated altitude. These climatic factors have nurtured lush and diverse landscapes within the city, including plateaus, valleys, and dense forests, all contributing to its captivating geological setting. The intersection of this rich cultural heritage, religious significance, unique climate, and diverse natural landscapes makes Kandy an intriguing subject for our study, which seeks to delve into the perceptions and significance of urban vegetation in this UNESCO Heritage City. Understanding the relationship between the city's rich heritage and its green impressions will shed light on the broader discourse of urban sustainability and cultural conservation in a global context. As urbanization continues to rise, addressing public health concerns and mitigating the adverse effects of urban greenery, such as stress-related issues, has become imperative. This research focuses on human perception as a crucial parameter to incorporate into urban street corridor vegetation planning and land-use policies. The goal is to preserve green areas in urban ecosystems.

Aims:

The primary aim of this research is to investigate the intricate relationship between humans and their environment within a cityscape, particularly addressing the common misconception that human activities tend to override natural processes. Specifically, this study aims to focus on the city of Kandy, a UNESCO World Heritage City, to better understand the interplay between human perceptions and the planning of vegetation belts in urban street corridors.

Objectives:

To achieve the overarching aim, this research will pursue the following specific objectives:

Assess the Existing Vegetation Belts in Kandy's Grid City Area: Conduct a comprehensive evaluation of the current state of vegetation belts within Kandy's Grid City area, considering their types, distribution, avifaunal networks, and overall condition.

Identify Human Perceptions and Preferences Regarding Vegetation Belts in Kandy: Collect data through surveys, interviews, or other appropriate methods to ascertain the perceptions, preferences, and attitudes of the local population in Kandy regarding vegetation belts within their city.

Identify the human perception-based parameters for developing the Criteria for Vegetation Belts in Urban Street Corridors: Based on the assessment and feedback obtained, develop a set of planning criteria and guidelines for the establishment and maintenance of vegetation belts in urban street corridors in Kandy.

2. Methodology

2.1 Field Survey

A comprehensive field survey was conducted during the 2020–2023 period within the grid city area to identify the vegetation status distribution pattern and avifaunal networks of the vegetation belts. Bird and plant species identification was conducted based on binomial nomenclature to avoid any ambiguities.

2.2 Questionnaire Survey

A questionnaire survey was meticulously executed with a sample size of 100 participants, comprised of two distinct respondent categories in August–September 2023: urban residents and tourists, both domestic and international. The objective of this survey was to elicit and analyze perceptions and opinions regarding the presence of vegetation belts in the city of Kandy.

The survey was conducted utilizing the Survey Nuts online platform, allowing for the collection of valuable insights and perspectives concerning the vegetation belts within the historical Kandy Heritage City. Data collection was carried out through two distinct methods: an online survey conducted via smartphones within the local community and a face-to-face questionnaire administered among non-smartphone users in the community.

3. Results and Discussion

3.1 Initiation of vegetation belts in Kandy's Grid City area

In response to the growing awareness of the environmental challenges posed by urbanization and in alignment with Sri Lanka's "National Physical Planning Policy and the Plan-2017-2050" (NPPPP-2017-2050), urban areas have increasingly recognized the imperative of sustainable development. Kandy, a UNESCO World Heritage City celebrated for its historical, cultural, and environmental significance, embarked on a visionary journey to enhance its urban greenery. This transformative initiative began in 2018, with a notable focus on establishing vegetation belts along road corridors within the city's grid areas.

The driving force behind city administration is Kandy evolving into a "Green Heritage City" where residents and visitors alike can relish the benefits of urban greenery: "a shade for the head, fresh air for the lungs, and a cool environment to enjoy the beauty of the city." They collectively acknowledged the deteriorating air quality in the city, leading to the launch of a tree-planting project in 2018. The momentum of this initiative was temporarily stymied by the unforeseen challenges posed by the COVID-19 pandemic. Innovatively, at present, it introduces a ground-breaking approach to sustain and expand the tree-planting project. This novel concept involves active participation from the general public, who now have the opportunity to directly fund and contribute to the city's green transformation. Under the banner of 'Magen Gasak Mahanuwarata' (A tree from me for Kandy), this inclusive approach not only empowers the community but also underscores the collective commitment to making Kandy a greener, more sustainable urban environment. As Kandy embraces this transformative path, it not only contributes to its ecological well-being but also sets an example for urban centers worldwide seeking to balance urban development with environmental conservation. Anyhow, planted trees are growing fast due to the favorable climate in recent years, and several arguments concentrate on this street corridor vegetation.

3.2 Current status of the tree belts

Based on the results of a field survey conducted between August and September 2023 within the grid city area, a total of 34 distinct vegetation belts have been identified. These vegetation belts are characterized by the presence of trees with a height ranging from 15 to 20 meters and a perimeter measuring approximately 40 to 60 centimeters. Notably, the vegetation in this area exhibits a diverse composition, featuring plant species of both ecological and medicinal significance.

The vegetation diversity is primarily composed of several noteworthy species, and they are mentioned below.
These species are valued for their medicinal properties and contribute to the overall ecological richness of the area. Additionally, the survey has revealed the presence of flowering trees, which add aesthetic and environmental value to the region.

Table 1: The vegetation diversity in the Kandy Grid City Area

Medicinal and other Plants	**Scientific Name**	**Flowering plants**	**Scientific Name**
Karanda	*Pongamia pinnata*	Esala	*Cassia fistula*
Mee	*Madhuca longifolia*	Jacaranda	*mimosifolia*
Kohomba	*Margosa – Azadirachta indica*	Flamboyant or flame tree	*Delonix regia*
Kumbuk	*Terminalia arjuna*	Kahamara	*Peltophorum pterocarpum*
Pink Poui	*Tabebuia rosea*		
Pihimbiya	*Filicium decipiens*		
Mahogany	*Swietenia mahagoni*		
Mara	*Samanea Saman*		
Mango	*Mangifera indica*		
Etteriya	*Murraya paniculata*		
Boo Tree	*Ficus religiosa*		
Frangipani	*Plumeria*		

Furthermore, the study has indicated that the diverse array of plant species plays a significant role in the mitigation of environmental pollutants. This is achieved through the effective removal of pollutants by the leaves of these various plants, underscoring the ecological importance of the area.

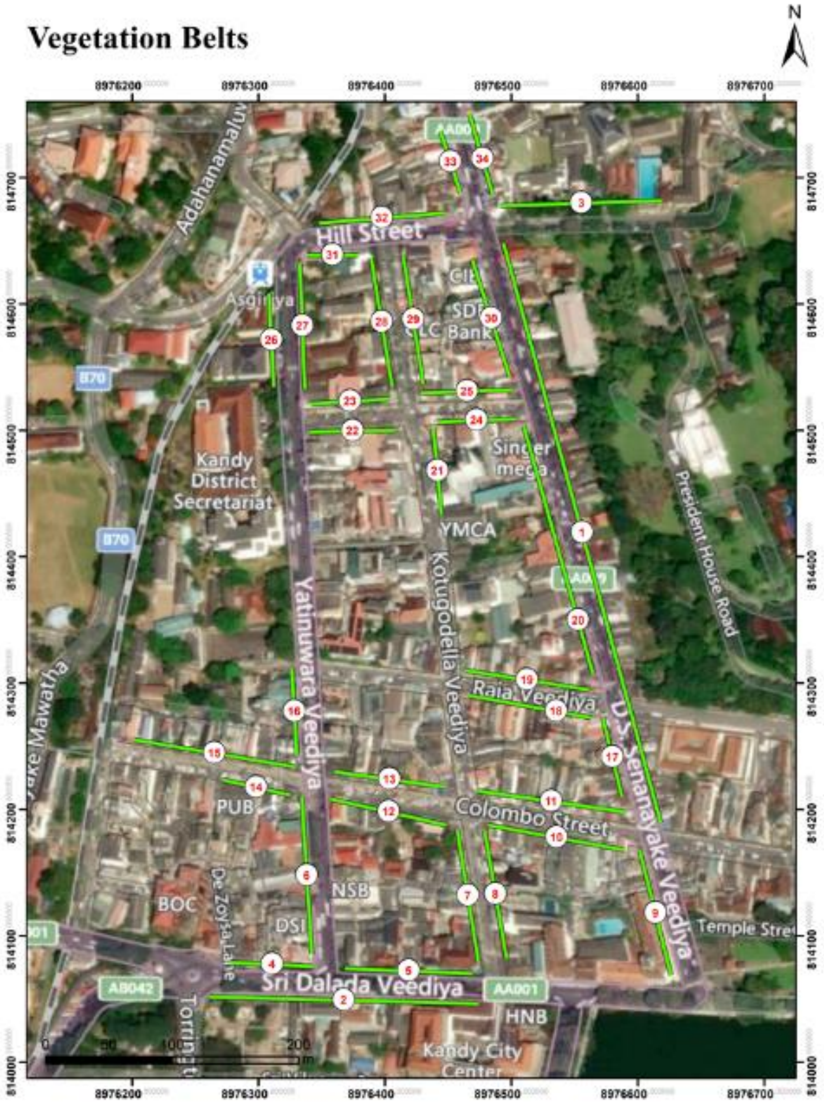

Figure 1: Vegetation belts in Kandy's Grid City area (2023).

3.3 Bird diversity

Among the bird community species richness was approximately five. Water birds such as cormorants were observed on top of the tree branches adjacent to Kandy Lake. Apart from that, four other landbird species were noticed: Ceylon Crow, Rock Pigeon, Common Mina, and House Sparrow. Amongst them, Common Crow showed the highest abundance and could be spotted everywhere throughout the grid city—upon rooftops, electric cables, roaming on the pavements, upon the trees, etc. However, most of them seemed to stay on the huge old trees, especially those aligned with Sri Dalada Veediya. Therefore, the floor beneath the trees found in this area was covered with bird fecal matter and their plumage. It has become such a nuisance in the sense that it can disturb the cleanliness and aesthetic beauty surrounding the heritage city. Every morning, it was observed that the benches located in front of the Kandy Lake were thoroughly cleansed with water by the sanitary workers, only to be covered with birds' droppings by the evening.

Table 2: Bird Diversity in Kandy Grid City Area

Common Name	Scientific Name
Ceylon Crow/ Colombo Crow	*Corvus splendens*
Common myna	*Acridotheres tristis*
House Sparrow	*Passer domesticus*
Little Cormorant	*Phalacrocorax Niger*
Rock Pigeon	*Columba livia*

3.4 Green Impressions: Vegetation belts in Kandy's Grid City area

According to the survey, 48.28% of city dwellers and visitors visit Kandy city for shopping, to meet friends, and for other activities, as Kandy is the hub for many need-based companies. The regular visiting percentage is 41.38% as some are working in Kandy City and going for the day to day activities. Rarely visiting are foreigners, people who are living abroad, and other people who are working in other districts in Sri Lanka.

When considering the intriguing insights provided into urban vegetation, approximately 45.61% of respondents expressed very positive and somewhat positive views, emphasizing the aesthetic appeal of urban greenery. Many respondents underscored the role of vegetation in providing fresh air and shelter. A smaller percentage remained neutral (5.26%), indicating ambivalence, while 3.51% conveyed a negative impression. The below chart illustrates the spectrum of responses, encompassing both positive and negative of the city dwellers and the pedestrians.

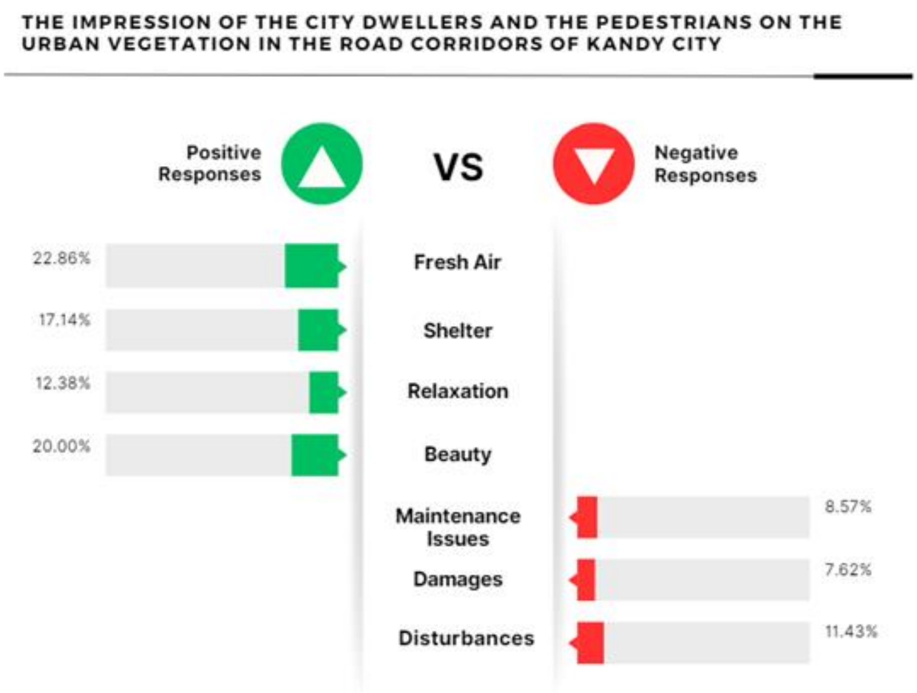

Figure 2: Impression of the city dwellers and the pedestrians on the urban vegetation in the road corridors of Kandy City (2023).

In the eyes of the people, urban vegetation has a profound positive impact, offering respite from air pollution in Kandy, a plateau city characterized by high pollution levels. Many also appreciate the shelter that urban vegetation provides, ameliorating the warm conditions within the city's grid area and benefiting building owners, residents, and pedestrians. This natural coolness reduces the need for excessive electricity consumption for cooling. In addition to shelter and fresh air, respondents acknowledged the aesthetic value of urban greenery, noting its contribution to the beauty and mental relaxation of Kandy City. A participant eloquently encapsulated the sentiment by noting, "It's providing not only beauty but also relaxation with fresh air. Now, it seems there is a substantial air pollution problem in the town. This vegetation might be a valuable tool to mitigate this issue."

Furthermore, urban vegetation has played a pivotal role in providing shelter to the city's residents. Before the introduction of green spaces, Kandy's urban landscape was characterized by an abundance of concrete structures, contributing to elevated temperatures and discomfort, especially during the daytime. Urban vegetation has significantly ameliorated this issue, providing refuge and relief to both building occupants and pedestrians. Notably, this natural shelter has brought about a reduction in the demand for energy-intensive cooling solutions, benefiting building owners by reducing electricity costs.

As one participant aptly pointed out, "Shelter, fresh air, relaxing, aesthetic value to the area, beauty, Reduced energy use, reducing the demand for fossil fuels; vegetation can be used to cool houses and commercial structures, reducing the use of polluting refrigerants." Beauty emerged as another prominent aspect of the positive perception of urban vegetation in Kandy City. Respondents frequently emphasized how the introduction of greenery had transformed the city's appearance, provided a source of mental relaxation, and enhanced the overall aesthetics. In their comments, they expressed sentiments such as, "Shelter is better than it was a decade ago. Fresh air is naturally scarce due to the town's location. Trees certainly add beauty to Kandy Town. Looking at trees is relaxing when having a coffee or tea in a restaurant in town." The positive results of this survey illuminate the vital role of urban vegetation in enhancing the quality of life in Kandy City. Aesthetically pleasing, environmentally beneficial, and essential for mitigating the adverse effects of air pollution, urban vegetation has received a resounding endorsement from a diverse group of participants. These findings underscore the significance of green spaces in urban planning and development, emphasizing their multifaceted advantages in creating a more liveable and sustainable city.

Considering the diverse perspectives shared by participants, it is imperative to consider both the positive and negative viewpoints on the urban vegetation within the city of Kandy. While many have expressed their admiration for the lush greenery adorning the cityscape, a significant portion of participants have offered critical insights that warrant thorough consideration. Among the detractors, the foremost concern centers around the maintenance of urban vegetation in Kandy. They emphasize that this is an issue that demands immediate attention. Given the city's high population density during daylight hours, there is a heightened risk of potentially dangerous incidents occurring. Specifically, these concerns revolve around perilous occurrences such as falling branches or trees, posing threats to individuals, buildings, vehicles, and the invaluable ancient monuments that adorn this heritage city, particularly during rainy seasons.

Notably, the proximity of trees and their branches to these ancient monuments is perceived as a potential source of damage. A prevailing belief also exists among some stakeholders that the presence of urban vegetation may decrease property values due to apprehensions related to falling branches, leaf litter, or obstructed views. Furthermore, the presence of urban vegetation can inadvertently attract pests like insects, rodents, and birds, creating a nuisance and potential health hazards for the populace.

One noteworthy observation stemming from the field survey is the displacement of bird populations from the lakeside trees to street corridors adorned with trees. While the intent may have been to provide a conducive habitat for these avian creatures, it has unintentionally raised concerns about potential damage to historical monuments. Another point of contention raised by participants is the placement of trees and large plants near sidewalks and roads, which, at times, obstruct visibility and create hazards for pedestrians. The resultant traffic congestion and inconvenience have led to mounting frustration among the city's residents and visitors alike. Additionally, the potential for infrastructure damage looms large, as tree roots can undermine sidewalks, roads, and underground utilities, necessitating costly repairs and ongoing maintenance efforts.

The sentiments of these city dwellers and pedestrians underscore a common thread of concern for the preservation and management of Kandy's unique urban landscape. As one participant aptly puts it, "It (the vegetation) is not suited for the present town setup." The sentiment is echoed by another who laments, "I don't think that I've experienced those many positive urban vegetated road corridors in Kandy City." Moreover, the overshadowing of building facades, particularly those of protected monuments, is seen as a significant challenge, impacting the historical and aesthetic aspects of the world heritage city of Kandy.

“Sometimes those trees cover the building facades of protected monuments, which are very valuable aspects of the world heritage city of Kandy.” Recognizing the city's status as a heritage hub and attracting numerous tourists, participants highlight the paramount need for meticulous consideration of maintenance and management practices to ensure that the rich cultural and architectural heritage of Kandy is not compromised.

The discourse surrounding urban vegetation in Kandy City reflects a complex interplay of benefits and drawbacks. While the greenery enhances the city's charm and liveability, concerns regarding maintenance, safety, infrastructure, and the protection of heritage sites necessitate a thoughtful and comprehensive approach to managing the urban vegetation in this culturally significant city. The input from various stakeholders highlights the importance of striking a balance between these contrasting perspectives to ensure the sustainable development and preservation of Kandy's unique urban environment.

4. Challenges and Recommendations

4.1 Challenges

Shortly, the burgeoning road corridor development poses a significant challenge to the picturesque city of Kandy, a challenge primarily centered around the management of its vegetation. The imperative lies not only in optimizing positive outcomes but also in minimizing the potential negative repercussions. Kandy, a city steeped in historical significance and architectural heritage, finds itself grappling with a complex dilemma.

Old and majestic trees have long graced the city's landscape, with prominent specimens adorning iconic thoroughfares such as Dalada Veediya and Yatinuwara Veediya. Yet, the year 2018 saw the introduction of a novel initiative: the planting of new trees along narrow pedestrian roads. Fast forward to the present, and these arboreal additions, now nearly five years old, have become a source of concern, with the potential for grave ramifications.

The pernicious impact of these new trees extends beyond aesthetic considerations. Their growth threatens the very fabric of Kandy, imperiling the structural integrity of buildings, the stability of pedestrian pavements, and the functionality of the underground drainage system. This, in turn, poses risks to the well-being of the city's inhabitants.

One salient issue lies in the suitability of the tree planting method employed in Kandy. While it may be ideal for cities with broader pedestrian streets, where there is ample space for the trees to flourish and expand their roots, Kandy's more confined urban setting necessitates a more meticulous approach. The encroachment of branches upon buildings and the destructive potential of roots for pedestrian roads emerge as pressing concerns that demand immediate attention.

The historic underground drainage system, a relic of the British colonial era, adds a layer of complexity. In a city adorned with ancient monuments and architectural wonders, any damage inflicted by burgeoning vegetation can have far-reaching consequences. The challenge of sourcing skilled labor and materials that can accurately replicate the methods and materials used in constructing these age-old structures is formidable.

Furthermore, the repercussions extend to the populace, both local and international, who traverse Kandy's streets. Falling trees and branches pose a direct threat to public safety, endangering lives and property. Kandy, as a significant tourist hub, cannot afford to compromise the safety and well-being of its visitors. The disruption caused during maintenance activities only exacerbates the predicament, inconveniencing pedestrians and potentially affecting the city's image as a hospitable destination.

The challenge posed by the changing vegetative landscape in Kandy is multifaceted and requires immediate attention. Balancing the preservation of historical heritage with the evolving urban environment presents a delicate conundrum, which, if not addressed judiciously, could jeopardize the city's character and safety. Careful planning, adaptive solutions, and proactive management are imperative to navigate these complexities and ensure a prosperous and harmonious future for Kandy.

4.2 Recommendations

The advent of negative responses to the vegetation along the road corridors of the illustrious heritage city of Kandy presents an array of challenges, necessitating prudent solutions to circumvent potential pitfalls. The preservation of the city's unique character and heritage must be harmonized with contemporary urban challenges. In this context, the implementation of potted bonsai trees emerges as a favorable recommendation.

Potted bonsai trees offer an elegant solution to the challenges posed by the current vegetation. Their compact nature and controlled growth make them an ideal choice, mitigating the risk of disruptive growth and root expansion. The controlled height and root growth of potted bonsai trees not only preserve the city's aesthetic appeal but also protect against structural damage to buildings and disruption of pedestrian infrastructure.

Furthermore, the recommendation of bushes instead of growing trees is a practical and efficient approach to urban landscaping in Kandy. Bushes are inherently low-maintenance and do not impose the risks associated with towering trees. Their adaptability to confined spaces ensures that they can be thoughtfully integrated into the city's design without compromising on aesthetics or safety.

To safeguard against urban flash flooding, a recurrent concern in this heritage city, the proposition of rainwater harvesting on rooftops emerges as a strategic measure. This dual-purpose approach not only addresses the issue of flash flooding but also optimizes the utilization of limited space. Rainwater harvesting systems create an opportunity for the cultivation of potted vegetation on rooftops, an innovative solution that marries environmental sustainability with urban beautification.

By encouraging rooftop potted vegetation, Kandy can harness the multiple benefits of vegetation without sacrificing space on the ground, where there are constraints related to infrastructure and heritage preservation. This strategy not only bolsters the city's resilience against flooding but also contributes to the creation of a green urban landscape, enhancing the overall quality of life for its residents and visitors.

As Kandy grapples with the intricate challenge of balancing heritage preservation and urban development, prudent choices regarding vegetation and sustainable practices can pave the way for a brighter future. The introduction of potted bonsai trees, the cultivation of bushes, and the implementation of rooftop rainwater harvesting are strategic steps towards safeguarding the city's heritage while addressing contemporary urban challenges and securing a thriving future for the Heritage City of Kandy.

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INFLUENCE OF URBAN PARKS ON URBAN THERMAL ENVIRONMENT – A CASE STUDY: INTERMEDIATE ZONE & ARID ZONE IN SRI LANKA

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Abstract: Urban parks are a type of green infrastructure that can be introduced as a significant solution to replace the declined greenery in an urban environment, and they have emerged as potential strategies to mitigate adverse effects of urban thermal conditions. Evaluating the performance of urban parks is mandatory in tropical conditions, as it indicates the research gap. In this study, thermal performance, Relative Humidity (RH) & CO_2 concentration were quantified for a selected park in an intermediate zone, in Sri Lanka. An in-situ experimental study considered air temperature, RH & CO_2 & simulation study was conducted for the arid zone. The simulation study examined the impact of the thermal environment on urban parks by modeling a designated site with ENVI-met 5.1.1.0 microclimate software. The model was validated by observed values & simulated values. R-Squared (R^2) value for temperature was 0.95. The model was used to generate microclimate data for two scenarios the existing condition and after the installation of an urban park in the selected area in an Arid zone of Sri Lanka. An occupant satisfaction survey was executed to assess the performance of the urban park & awareness of the Urban Heat Island effect for the Intermediate zone. The study revealed that the maximum temperature reduction of the selected urban park was 4.72˚C. Recorded RH values were mostly lower than in the city & CO_2 levels showed fluctuations with time. The questionnaire survey revealed that 78% of people were highly satisfied with the urban park. The simulation study showed a 2.47 ˚C maximum temperature reduction that reveals the value of urban parks in an urban thermal environment. According to the study, urban parks can be identified as a very effective green infrastructure for reducing urban heat while ensuring human well-being. Thus, the influence of the urban parks for tropical conditions should be further studied and the knowledge should be used for the design of sustainable cities.

Key words: CO_2 concentration; ENVI-met; Occupant satisfaction; Relative Humidity; Urban parks; Urban thermal comfort

1. Introduction

At present, the global population residing in urban regions surpasses that in rural areas. As of 2018, 55% of the world's populace lived in urban settings. This translates to a total of 4.2 billion individuals residing in urban communities, in contrast to 3.4 billion in rural ones. Over the years, the world's population has undergone rapid urbanization, a trend that has been evident since 1950. In 1950, over 70% of the global population inhabited rural areas. However, in a significant milestone achieved in 2007, the urban population worldwide exceeded the rural population for the first time in history. Subsequently, the urban population has continued to grow at a faster pace than the rural population(United Nations, 2018). The present urban population has been estimated as 57% of the total world population(Population Reference Bureau, 2022).

The swift process of urbanization stands out as one of the foremost human-induced elements that have a profound impact on ecosystems and the overall concept of sustainability(Jiang & O'Neill, 2017). The conversion of land through urbanization represents a particularly severe challenge, often leading to significant environmental issues. The process of urbanization frequently gives rise to substantial environmental problems(Bettencourt & West, 2010). These encompass water scarcity, emissions of greenhouse gases, depletion of biodiversity, the formation of urban heat islands, and the spread of environmental pollution across urban and nearby regions(Forman and Wu, 2016; He et al., 2019).

One of the swiftly observed outcomes resulting from land conversion within urban regions is the alteration of Land Surface Temperature (LST), coupled with the emergence of the Urban Heat Island (UHI) effect. UHI refers to the disparity in surface temperature between the central urban zone and the surrounding non-urban periphery(Voogt & Oke, 2003). Furthermore, the phenomenon of urban overheating is being exacerbated by both local and global climate change. This exacerbation results in an escalation of extreme temperature events (such as heat waves) in terms of their intensity, frequency, and duration. Consequently, urban residents are experiencing prolonged periods of thermal discomfort and heightened heat stress, leading to an increase in heat–related illnesses and fatalities(Mazdiyasni et al., 2019; Santamouris et al., 2017). According to the predictions, the existing thermal stress experienced by pedestrians in hot and humid climatic regions is poised to intensify to a degree where spending time outdoors will become nearly impractical(Harlan et al., 2014; Huang et al., 2018).

In recent times, Green Infrastructure (GI) has garnered attention as a practical and well-suited for mitigating and alleviating the UHI effect. This strategy has been adopted in numerous countries with positive results(Fan et al., 2019; Van Hove et al., 2015).GI can be defined as a "strategically planned network of natural and semi–natural areas(with other environmental features) designed and managed to deliver a wide range of ecosystem services" This refers to a networked system of green spaces encompassing various types, including urban parks, urban forests, green streets, green roofs and green walls(J. Wang & Banzhaf, 2018). Various types of GI fulfill distinct roles as integral components of the urban ecological system. Urban parks and urban forests serve as green points, while urban streets and green walls represent green lines. Additionally, urban forests are green polygons within the city, each exhibiting diverse shapes, sizes, and structures. Despite their differences, all these elements contribute to the broader green space system, offering a multitude of advantages to the city. Furthermore, these different GI types can be interconnected in a points-lines-polygons cascade system, working in synergy to amplify each other's functions, ecosystem services, and benefits(Bartesaghi Koc et al., 2018; Shafique et al., 2020; Zander S Venter et al., 2020).

Urban parks, which form a significant facet of green infrastructure within urban areas, play a pivotal role in facilitating outdoor recreational activities for city residents. Furthermore, they offer essential ecosystem services, including the cooling of land surfaces and the adjacent atmosphere(Aram et al., 2019; Shafique et al., 2020). Unlike the UHI effect, the cooler temperature patterns attributed to the presence of urban parks have been termed the "park cooling island" in certain previous research studies(Cao et al., 2010; Wang et al., 2018) and also the utilization of urban parks can foster enhanced social cohesion by encouraging emotional connections, boosting satisfaction with residential areas and facilitating increased social interactions(de Haan & Zoomers, 2005).

Assessing the cooling effect of urban parks as part of GI is of utmost significance for mitigating climate changes in cities (Akbari et al., 2016; Yu et al., 2023) in search of pathways for building sustainable cities. Many countries have assessed the cooling effect of green surfaces like China (Cao et al., 2021; Yu et al., 2017), Japan (X. Cao et al., 2010), Malaysia (Brown et al., 2015),

USA(Middel et al., 2016) and UK(Doick et al., 2014) etc. When considering the Sri Lankan context, most of the studies have been conducted to assess the psychological impacts of urban parks such as Diyatha Uyana (Lokuliyana, C.K. & Ratnayake, 2020; Oshani PAL, 2015) and Viharamahadevi Park (Gunawardhana et al., 2020; Pussella and Li, 2019) thus, a majority of studies have focused on investigating the effects of social, physical and psychological factors related to urban parks(Gunawardhana et al., 2020). There is currently a lack of a cohesive approach for upkeep, urban planning, or a sustainable outlook for the city, as a result, it has become imperative and essential to conduct an innovative exploration of the theory and practical implementation of urban green spaces, particularly within the framework of a developing nation such as Sri Lanka(Konau, 2016).

A lack of study area and depth was identified in the Sri Lankan situation for the evaluation of the thermal performances of urban parks and this research was designed to decrease the gap of research evidence for real urban parks in tropical conditions. This paper reveals the impact of Senanayake Park- Badulla as an urban park with the objectives (a) to quantify thermal performances and obtain the RH and CO_2 concentration profile of selected urban parks (b) to compare the urban park performances according to their typologies in practical application and (c) to evaluate the occupant satisfaction/perception for a selected urban park.

2. Materials and Methodology

The study was carried out at Senanayaka Park and Avenue – Badulla as a case study which representing the Intermediate zone. Instead of Badulla, the Hambantota Administrative Complex area was selected for the simulation study which represents the Arid Zone in Sri Lanka. As the study was designed for tropical conditions; the Badulla context was considered for the proceedings. The study consists of an In-situ experimental study with a Simulation and Questionnaire survey.

In-situ experimental study

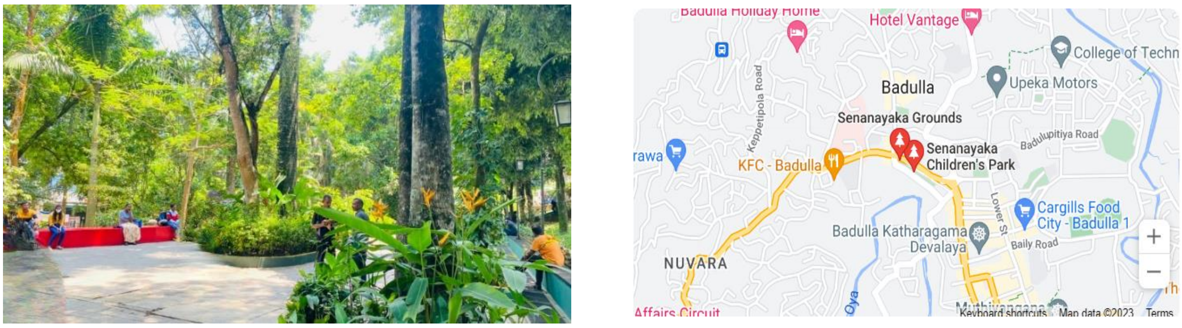
The thermal environment of the selected urban park was evaluated under this stage. Temperature variation, Relative Humidity, and Carbon Dioxide concentration profiles are the three main factors considered to determine the thermal environment of this Green Infrastructure. – A situ experimental study was conducted under two segments studying the basic characteristics of the park and performance evaluation of the park. Under basic characteristics of the park identification, the location of the park, plant types used, the orientation of the plants/trees, condition of the plants, surrounding conditions of the park, and the variation of population density with days of the week were identified.

Selected sites for the study:

Senanayake Park & Avenue

Senanayaka Park and Avenue is a small-sized urban park with an Avenue consisting of a children's park, located in the center of Badulla city (6°59'24.4''N 81°03'19.8'' E). The park consists of various types of large trees also bushes, vines, and shrubs. The vegetation was oriented systematically keeping a space for the avenue and the middle line of the park consisted of large trees, bushes, and shrubs. The park is surrounded by a crowded environment with government institutions like a police station, Municipal Council, Court complex, District Secretariat office, Election office, Banks, and Private Buildings. When considering the population variation within the park, the morning and evening time were crowded due to school time, hospital visitors and people tend to spend time leisurely in the evening.

The park was crowded during weekends when compared with weekdays especially because of the tuition classes, market visitors, and kids for the children's park.



(a) (b)

Figure 1: Senanayaka Park and Avenue (a) Inside of the park (b) Location of the park.

Hambantota Administrative Complex Area:

Hambantota Administrative Complex, located in the way of Gonnoruwa – Meegahajandura (6°09'57.8"N 81°07'37.2" E), the place was selected for the simulation study, representing the arid zone of the country. The complex area is crowded with the people who visit there to get the services from government institutes. The people suffer from extreme heat because the area doesn't have enough vegetation cover.

(b)

(a)

Figure 2: Hambantota Administrative Complex (a) satellite image (b) location in the map.

Temperature measurements

The site was assigned 36 hours (3 days 12 hours per day) for temperature measurements using a data logger which was calibrated by the National Building Research Organization (NBRO) as presented in Figure 8. Several temperature measuring points around the park were taken based on the (Galagoda et al., 2018; Yilmaz et al., 2018) study. The Data logger was installed at 1.8m height from ground level using a stand and a continuous power supply was required to run the machine accurately.

Relative Humidity (RH) and CO_2 concentration measurements

Temperature /RH/CO_2 data logger was used to measure these two parameters for selected three days, morning to evening; 0600h to 1800h. Data was recorded one one-second intervals for the case study and then the recorded data was averaged for hours.

Questionnaire survey

The purpose of this section was to evaluate the park visitor's satisfaction and their perception of urban parks. People who visit and hang around the park are considered as the audience for this case study. The questionnaire was prepared including major four segments, personal details, Personal observations and opinions, Awareness of the Urban Heat Island effect, and Suggestions, opinions, and recommendations for improvement of the park. 50 people's responses were considered for this evaluation. Questionnaires were distributed randomly to selected park visitors representing the selected day time of the day with 58% female participants and 42% male participants.

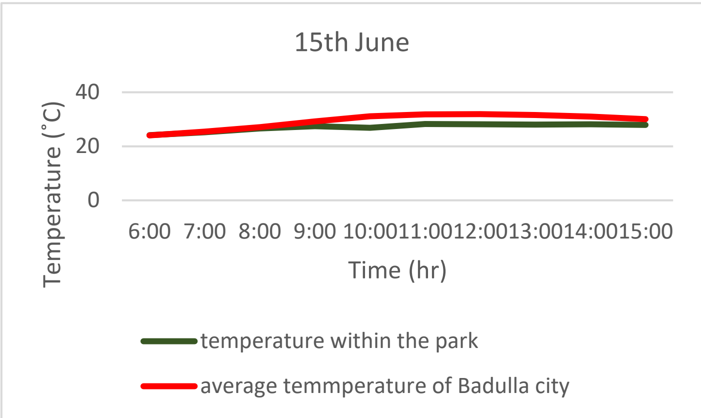
Simulation study

ENVI-met 5.1.1.0 was used for the simulation study. A case study (Administrative Complex premises – Hambantota) was selected to simulate the outdoor thermal condition with an urban park. Created 3D models of the urban park were validated with the manual temperature measurements and previously conducted software calibration results were considered which were done for tropical Sri Lankan conditions successfully. (Herath et al., 2018; Perera et al., 2021).

3. Results and Discussion

Thermal performance of the park

Hourly averaged temperature for Senanayake Park and Avenue is shown in Figure 3 compared to the temperature of Badulla city which was obtained from satellite data.



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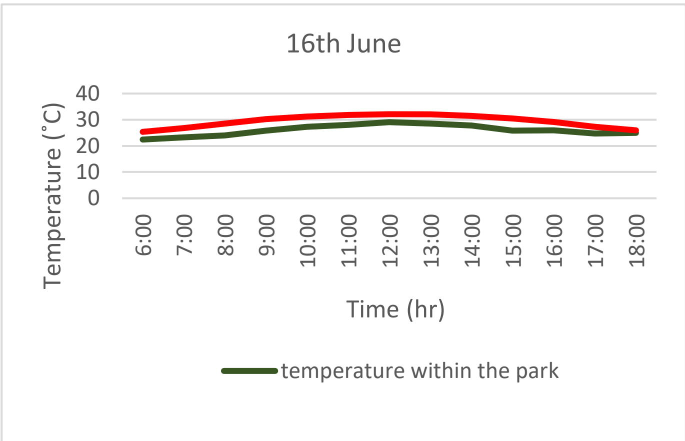

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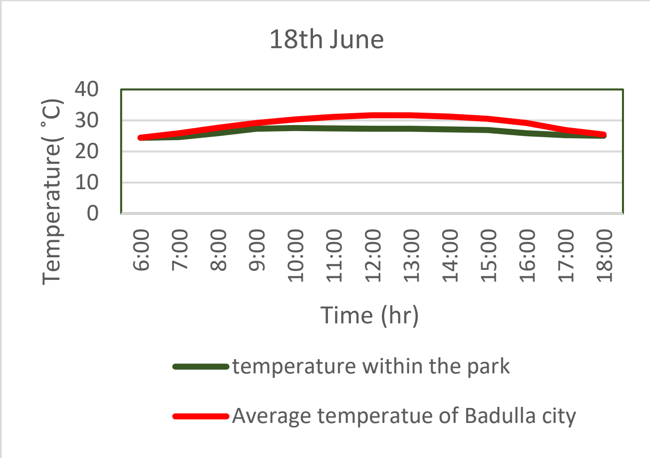


(c)

Figure 3: Temperature differences between urban park and Average temperature of Badulla city (a) 15th June (b) 16th June (c) 18th June.

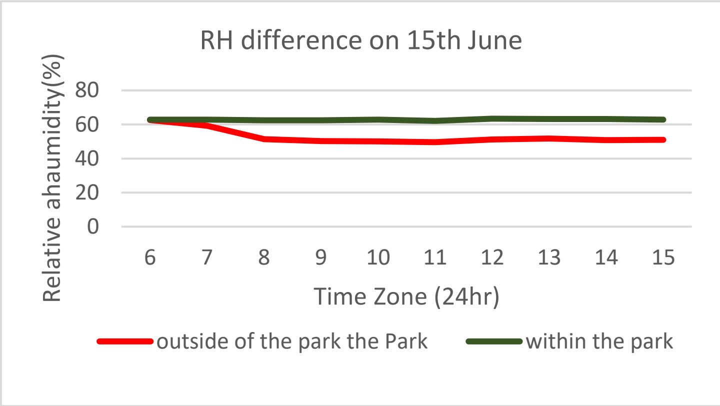
The maximum difference between the park and city temperatures was 4.27˚C at 1000h on 15th June, 4.72˚C at 1500h on 16th June, and 4.35˚C at 1200h on 18th June. According to the statistical analysis results (0.038, 0.0006, 0.002 p values for the 15th, 16th, and 18th of June respectively), it showed significant temperature reduction (p value< 0.5) from the park compared to the city throughout the day.

There was a similar study was done for urban parks in Bhopal, India showed 3.1˚C, 0.4 ˚C, and 6.7 ˚C temperature reduction compared to the other areas in the city according to their field measurements (Ali & Patnaik, 2018) and also another case study which was done for Taiwan's urban parks in summer period showed about 9 ˚C temperature difference (Hsieh et al., 2016; C. L. Tan et al., 2015; Priya and Senthil, 2021).

This phenomenon can be influenced by the process of evapotranspiration from plants, along with the presence of impervious surfaces. This led to a decrease in surface temperature and emission of long-wave radiation from the surface(Ali & Patnaik, 2018). Thus, this cooling effect happens due to the combined impact of shading and evapotranspiration (Shashua-Bar & Hoffman, 2000). When considering the vegetation cover of urban parks, the density of the canopy, the extent of the canopy coverage, and the height of trees additionally contribute significantly to the cooling influence (Bowler et al., 2010) and also the selection of plant species can impact the degree of temperature reduction, as various species possess distinct evapotranspiration and surface area characteristic, which affect their effectiveness in cooling(Tan et al., 2015). Based on the above results, the potential urban park temperature reduction range has been calculated as 2.27 ˚C – 10.07 ˚C.

Relative humidity profile for the urban park

The following Figure 3 shows the RH variation to time (0600h to 1800h) for the three days. All the graphs showed a trend of lesser RH around noon than in morning and evening and the recorded RH values for the park were higher than the RH values for the city.



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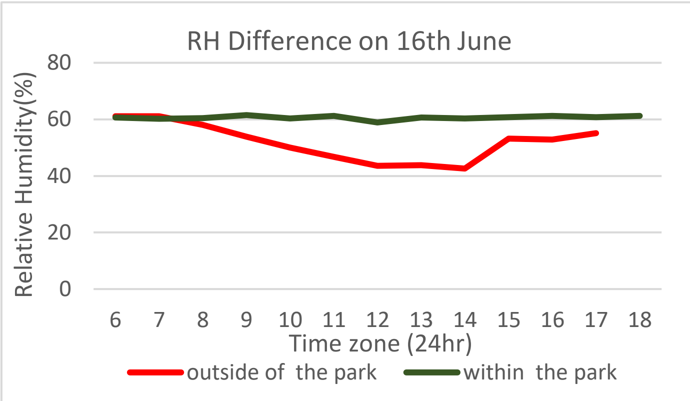

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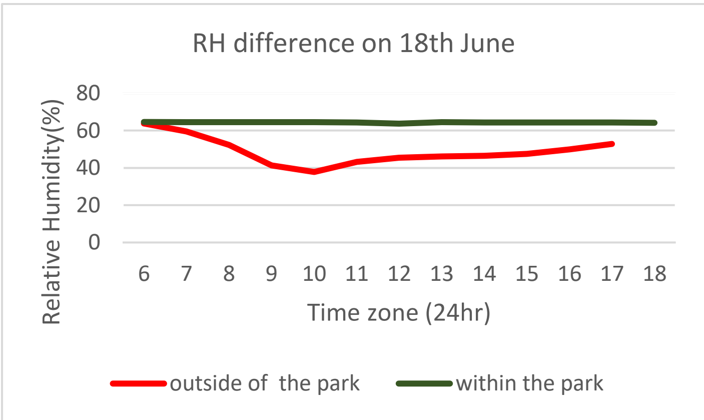


(c)

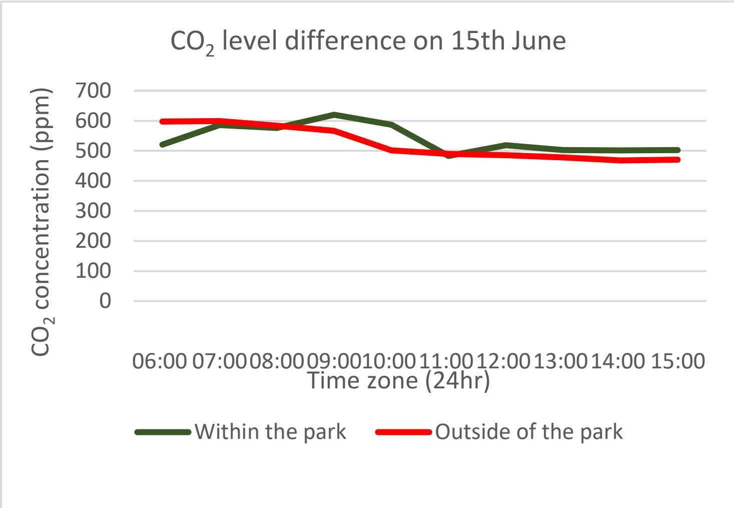
Figure 4: Relative Humidity differences between the urban park and the Badulla city area (a) 15th of June (b) 16th of June (c) 18th of June.

Calculated P values were 15th June 1.21131E-06, 16th June 9.20285E-05, and 18th June 2.74853E-07, and the maximum RH difference between the park and city area was 26.7%. RH can be identified as an important factor that influences human thermal comfort(Arghavani et al., 2020). Studies found that humans feel comfortable in the RH range of 30-65% (de Freitas & Grigorieva, 2015). According to the results, the park, and the city both showed desired RH ranges but most of the time the park showed higher RH values. The same study was done for Beijing Olympic Park, China for the building area, and the park showed an 18.8% RH difference in autumn (Kuang, 2020). In another study done for Almada municipality, Lisbon, Portugal green spaces showed 2-8% average increasing moisture conditions with compared to grey areas(Grilo et al., 2020).

The vegetation content of urban parks undergoes evapotranspiration the humidity level will increase within the park (Kuang, 2020) so that, increased tree canopy area causes to decrease in temperature and an increase in RH (Grilo et al., 2020). According to the recorded data, we can determine that the concentrated vegetation in the park influenced the RH level when compared to the city area.

CO_2 Profile for the park

Figure 5 depicts the Carbon dioxide concentration profile for Senanayake Park and Avenue.



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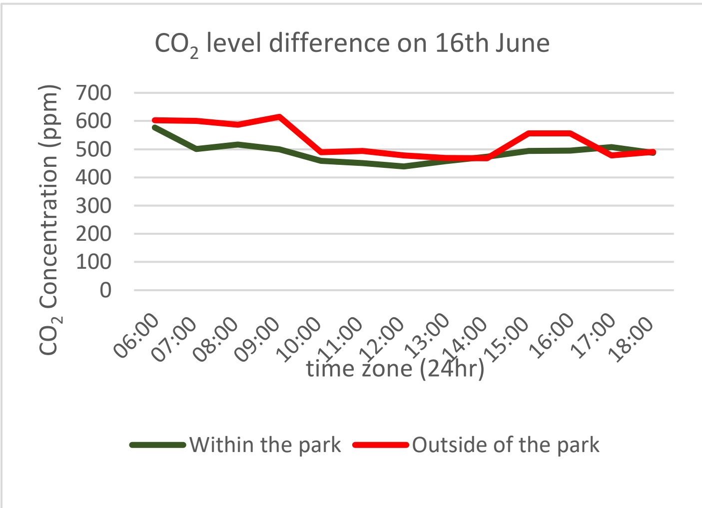

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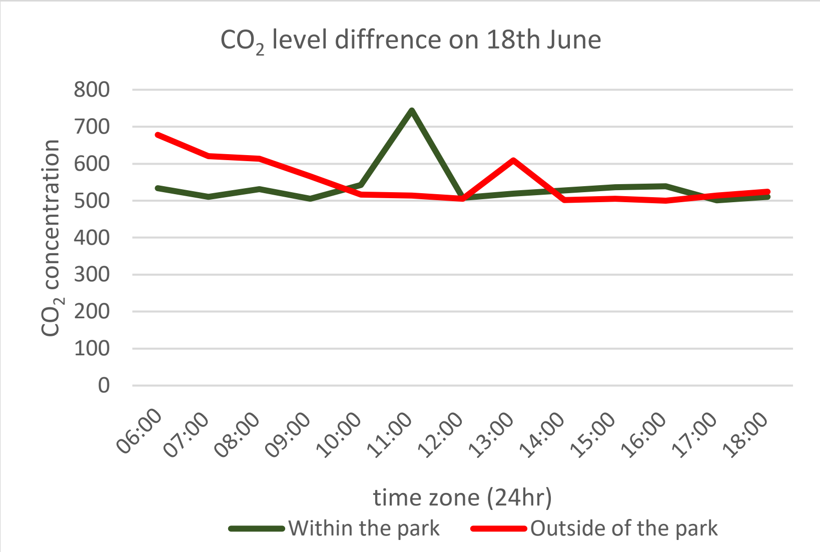


(c)

Figure 5: Carbon dioxide differences between the park and Badulla city area (a) 15th June (b) 16th June (c) 18th June.

According to the recorded data, the average CO_2 concentration reduction was 2.29% during the daytime. However, the concentration difference for the three days showed P values as 0.502, 0.041, and 0.615 for the 15th, 16th, and 18th of June respectively. Only 16th June showed a significant difference in the CO_2 levels between the park and the city area. Most of the time the CO_2 level within the park was lower than the city. But sometimes the CO_2 level was increased than the city, especially in the noon and evening times.

Results of the Questionnaire survey

Important characteristics of the considered sample for the questionnaire consisted of park visitor's details and preferences and observations of the park and the sample consisted of 58% female participation and 42% male participation. The highest percentage (24%) of occupants were included for the age group of 25-35. Of the education level of the park visitors 50 of them, 26 visitors had their higher studies and most of them were AL students and also Most of the park visitors were unemployed because most of them were AL students and 76% of park visitors lived within the Badulla area and 24% were from outside of the city.

When considering the park visitors' frequency of visiting the park was reported as weekly, while the Same study done for Beijing Green Spaces, China reveals nearly 46% of people visit more than 10 times per month according to their survey(Ma et al., 2019). Analyzed results showed that most of the visitors came to the park to spend time, for mental relaxation, and close to nature. A similar study which was done as a case study for Diyatha Guyana, Colombo revealed 25.8% of visitors come to the park for relaxation, 20.2% for contact with nature, 17.3% for contact with family, and 13.9% for exercises(Oshani PAL, 2015) and according to the survey results done for Viharamahadevi park, Colombo revealed that 51% of people visit the park for relaxing and enjoying,32% for exercises (Gunawardhana et al., 2020). According to the results of the survey, it can be determined that most of the park visitors come to the park for recreational purposes. A study done for found that people visit urban parks mostly for recreational purposes(Razak et al., 2016).

The satisfactory level of the park among visitors reported that 46% of people were highly satisfied when they were within the park (P value <0.001) and their response was the effect of mental relaxation when they were within the park recorded as satisfied (P value <0.001) and they were highly satisfied with an urban park having in their town (P value <0.001).

The evaluation of visitor's perception of the facilities (playground, Outdoor area, walking path, public places, enjoying the area, Resting area, Outdoor workout areas, Pet-friendly environment, Wi-Fi availability, water, and sanitation) which was provided by the park revealed that Park visitors were satisfied most of the facilities which were provided by the park except Wi-Fi availability. The following figure 20 shows the results of the visitor's responses on facilities provided by the park. A similar study done for urban parks in the Colombo area (Katubedda, Kelimadala, Diyatha) revealed that privacy and security were the highest preference for Katubedda Park (50%), and Kelimadala visitors were not satisfied with the sanitary facilities provided by the park (8.9% satisfaction) (Lokuliyana, C.K. & Ratnayake, 2020).

Park visitor's perception of the park was evaluated in the current condition and before the construction of the park. Most of the park visitors gave positive feedback (62%) for the questionnaire. A similar study done to evaluate resident's perception and use of green spaces for selected places in Brisbane, Australia, and Sapporo, Japan revealed that 64.8% of people reported that green spaces are better for their recreational activities(Rupprecht et al., 2015). According to the collected data records, it can be determined that the people have more preference for the park in their minds.

According to the results, more than 50% of people think the park is important for the sustainability of the city. But most of the park visitors (62%) didn't have an idea of the UHI effect while 95% of park visitors had at least secondary education, and only 24% of people gave Yes as the answer to that direct question (Do you aware of the UHI effect?).

The majority (33 responses) of the people think the park matters to reduce the heat from outdoors, 29 responses for increased air quality, 27 for mental relaxation, 26 for extra beauty, and only 14 responses for reducing urban heat. It can be considered as the experiences they had when they were staying in the park according to their knowledge and attitudes. The same study done for GI in the Colombo metropolitan area found that 46% of people think it matters for the aesthetical value, 28% for air quality control, and 26% for temperature regulation(Galagoda et al., 2018).

According to the analysis of gathered suggestions and opinions, most of the people were suggested to install a proper waste management system and plant more trees and ornamental plants. Instead, they suggested reducing noise pollution, increasing water availability, and increasing space. Other than that, they suggested the walking path should be constructed without disturbance to the people who hang around the park, organize more awareness and entertainment programs within the park, install mini-libraries, and put awareness notices.

Results of the Simulation Study

Manually measured temperature and RH data inside the Senanayaka park were used to validate the created model with simulated temperature and RH values shown in Figure 6 with R^2 of 0.9538 for temperature.

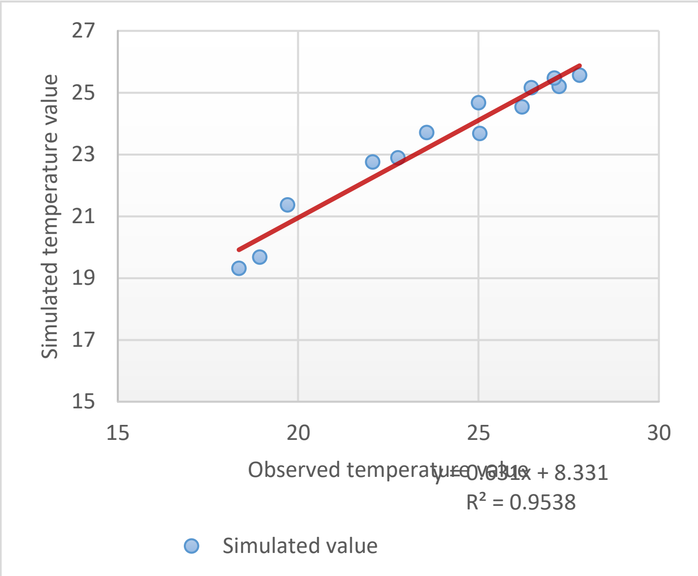
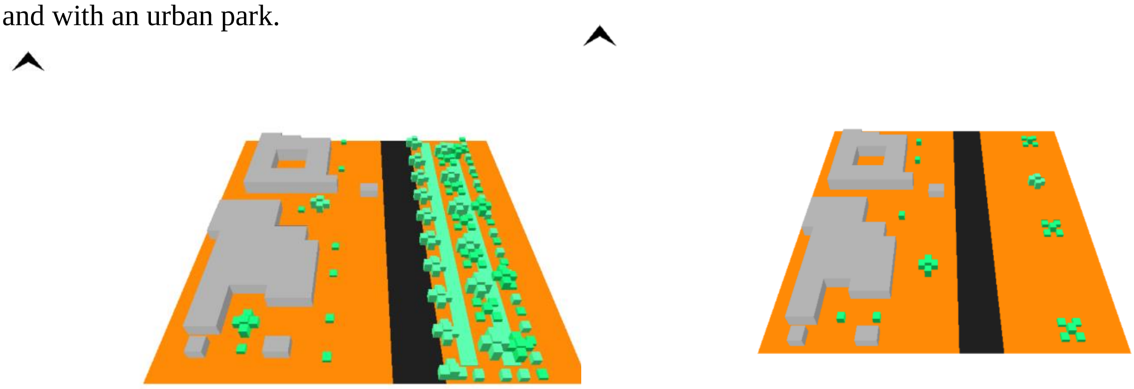


Figure 6: Regression line for the data validation.

Outdoor temperature changes within the park area were simulated. The 3D model of the Hambantota Administrative Complex considered for the simulation was created with and without an urban park (Figure 7). The modeled Administrative Complex without the green wall was simulated for outdoor thermal variation at first. The following figure shows the built models for HAC in existing conditions and with an urban park.



(a) (b)

Figure 7: Simulation models for the Hambantota Administrative Complex (HAC) (a) HAC with urban park (b) HAC without urban park.

Simulation results averaged with urban park condition for HAC recorded as 30.35˚C and for the existing condition of HAC averaged 32.82 ˚C. The temperature range variate from 25.31 ˚C to 33.46 ˚C by remarking a maximum peak level of 33.46 ˚C. Urban Park was capable of reducing the outdoor temperature from 2.47 ˚C. The prepared temperature contour maps were prepared through the analyzing tool (LEONARDO) in the ENVI-met application. The following Figure 7 depicts the temperature variation between two simulated models.

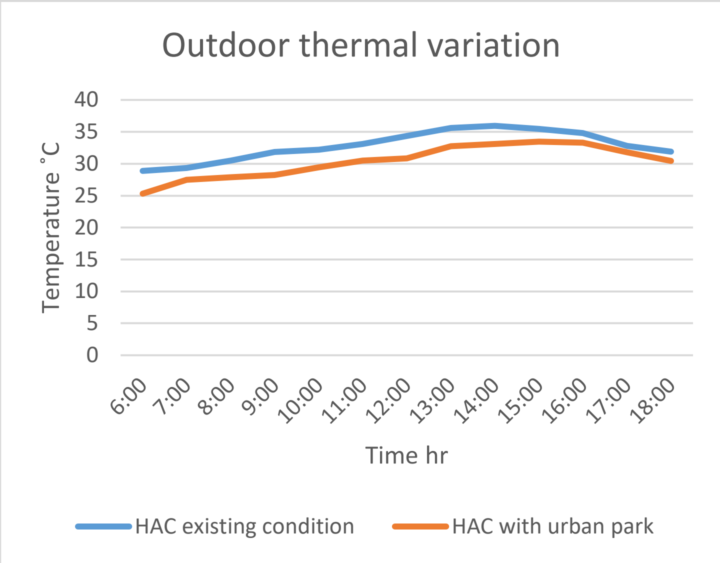


Figure 8: Differences in simulated outdoor temperatures.

A study done to evaluate the impact of green infrastructures by using ENVI-met in a tropical urban context, Colombo, Sri Lanka found that the maximum temperature reduction was 1.9˚C in an area of 4.58ha(Herath et al., 2018) and a similar study conducted for urban parks in Tehran, Iran found that 2.7 ˚C temperature reduction by the considered urban park according to their study(Karimi et al., 2020).

The highest temperature 33.46 ˚C may be a result of the thermodynamic characteristics of construction materials, lack of vegetation, and especially the arid nature of the HAC area. Materials with higher albedo, like asphalt used in roads, as well as cement and concrete bricks commonly found in buildings, possess the ability to capture solar radiation and subsequently emit this energy in the form of heat waves back into the surrounding environment. The thickness and composition of materials used to construct walls and roofing were considered during the simulations conducted in ENVI-met(Huttner & Bruse, 2009). According to the results, it can be determined that the vegetation cover has a significant impact in case of mitigating urban heat. A study done in the Glasgow Clyde Valley Region in the UK revealed that green cover could reduce surface temperature by up to 2˚C according to their simulation study done by using ENVI-met(Emmanuel & Loconsole, 2015). Tree Canopy Structure and Tree Coverage ratios also have an impact on the cooling capacity of vegetation (H. Wang et al., 2023) while the simulation study used several types of tree canopies to determine the impact. Instead of that the arrangement of vegetation also improves the microclimate and thermal comfort in urban parks (Li & Song, 2019). In particular, trees with a wide crown, large trunk height, and low albedo pavements provide more thermal comfort conditions in urban parks(Karimi et al., 2020).

Conclusion

Urban parks are very effective and highly applicable green infrastructure type in reducing heat stress in urban areas; especially at noon time (09:00h-14:00h). According to the case study the selected park showed a 4.72˚C maximum temperature reduction when compared with the city area. The RH profile showed a 26.7% maximum difference between the park and the city mostly due to high dense vegetation of the city. The CO_2 profile had some fluctuations when compared with the city due to the population variation inside the park. Mostly the park's CO_2 level was high in the evening and morning times because most of the park visitors were gathered at the park during that period.

According to the simulation study, an averaged outdoor temperature of 30.35 ˚C was obtained for the HAC with the urban park model and the park was capable of 2.47 ˚C of temperature reduction compared to the HAC in the existing condition model.

The questionnaire survey revealed that most of the park visitors lived within the city area (76%) and more than 50% of visitors were satisfied with the facilities which were provided by the urban park and also the safety within the park during day and nighttime. the visitors didn't have and clear idea of the programs that are organized in the park and only 30% of the people were aware of them. More than 60% of park visitors were satisfied with the park authority and they believe that the park authority is concerned about the problems regarding the park, and they work responsibly. The visitors had very lack of awareness of UHI and 62% of people had no idea about that concept. Lack of proper waste management methods was identified as the main burning issue for the park but more than 75% of people were satisfied with the park in their town.

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WATER POLLUTION AND WATER TREATMENT TECHNOLOGIES

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USE OF BULKING AGENTS FOR COMPOSTING SECONDARY SEWAGE SLUDGE FROM WASTEWATER TREATMENT PLANTS; A REVIEW

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Abstract: Due to the increasing number of centralized sewage treatment plants, sludge generation has increased in recent years, and disposal has become a serious problem. Sewage sludge is a biodegradable residue that contains a large amount of organic matter. Although the sewage sludge is rich in organic matter, the presence of pathogenic microorganisms, toxic heavy metals, and organic micro-pollutants restrict its use in field applications. Composting is a feasible solution for sludge disposal. However, high moisture content and low C/N ratio make sewage sludge composting a difficult task. Therefore, additional processes such as composting with bulking agents are proposed. Bulking agents are additional materials that can adjust the moisture content, C/N ratio as well and porosity of the sewage sludge. With the help of bulking agents, the sewage sludge can meet the optimal conditions for composting, and this makes the sewage sludge compostable. This paper reviews the effects of different bulking agents on the composting of sewage sludge and how each bulking agent differs from the other. Also, different composting methods that can be used to compost sewage sludge and composting conditions are discussed. Further, modifications recommended for improved performances of bulking agents are discussed.

Keywords: Sewage sludge; Composting; Bulking agents; NH_3 emission; Water absorbability

1. Introduction

Sewage sludge is a biodegradable residue released from the secondary treatment stage of municipal wastewater treatment plants (Malińska & Zabochnicka-Świątek, 2013). Due to the increasing number of centralized sewage treatment plants, the sludge generation has immensely increased and the disposal has become a serious concern. Although the sludge is rich in organic matter and biodegradable, the presence of pathogenic microorganisms, toxic heavy metals, and organic micro-pollutants restrict its use in field applications (Liu et al., 2020). Therefore, it would be useful to find a better solution for the treatment of sewage sludge.

Composting of sewage sludge for land applications has twofold benefits, providing a feasible solution for sludge disposal and generating a useful soil conditioner for agricultural purposes. However, the moisture content (MC) of the sewage sludge is very high and the carbon to nitrogen (C/N) ratio is very low (Malińska & Zabochnicka-Świątek, 2013). This makes the sewage sludge difficult to compost because it fails to meet the optimal conditions needed for composting. Therefore, it needs some additional materials that can increase the composting ability of sewage sludge. Those materials are called Bulking agents (Zorpas and Loizidou, 2008; Uçaroğlu, 2014; Zhou et al., 2014; Wu et al., 2015).

Bulking agents can adjust the moisture content, C/N ratio as well as the porosity of the sewage sludge (Zhou et al., 2014; Wu et al., 2015; Liu et al., 2020). Therefore, with the help of bulking agents, the sewage sludge can meet the optimal conditions for composting and this makes the sewage sludge as compostable. Most commonly used bulking agents are Sawdust, Straw, Woodchips, Cotton Wastes, Rice Hulls, Wood Shaving, Pine Leaves and Grass Clippings, etc, (Vanegas-Blandón et al., 2007; Zhou et al., 2014; Wu et al., 2015). Some novel bulking agents have also emerged in the recent past (Wu et al., 2015; Liu et al., 2020).

This study is to investigate suitable bulking agents for composting sewage sludge from Wastewater Treatment Plants and different composting methods for composting sewage sludge. Also, this study analyzes the effect of different bulking agents on composting sewage sludge, the modifications that can be added to improve performance, and how each bulking agent differs from others.

2. Sewage Sludge Composting

Sludge composting is a cost-effective and environmentally friendly method that is widely used for sewage sludge treatment (Li et al., 2013; Malińska, Zabochnicka-Światek and Dach, 2014; Nguyen and Shima, 2018). When sludge is composted, the organic matter in sludge is decomposed by microorganisms and forms a humus-like product which can be utilized as a fertilizer or a soil conditioner (Wong & Fang et al., 2000). According to Kosobucki et al. (2000), sewage sludge composting is the most preferred non-industrial method that can be used to treat sewage sludge. Also, this process stabilizes the sewage sludge chemically by destroying harmful pathogenic microorganisms and immobilizing toxic heavy metals which can contribute negatively to the environment (Hope, 1986; Zorpas and Loizidou, 2008). After stabilizing, the composted sludge contributes to supplying nutrients for the growth of crops and improves the structure of the soil to hold and absorb the nutrients (Vanegas-Blandón et al., 2007).

Sewage sludge composting is an aerobic process. Under oxygen-rich environments, the thermophilic and thermo-tolerant microorganisms degrade organic matter in sludge and release carbon dioxide and water as by-products (Parr et al., 1978; Sweeten et al., 2014). The operating conditions that are needed for composting are shown in Table 1.

Table 1: Operating conditions for sludge composting aerobically

Operating Condition	Optimal Range	References
Tempera-ture	Should be maintained at a thermophilic range $50-71$ ℃	(Fürhacker & Haberl, 1995; Sweeten et al., 2014; Wang et al., 2013)
Oxygen level	Atmospheric oxygen is around 5% or more in volume	(Sweeten et al., 2014)
Aeration	90-160 m^3/t.h	(Kosobucki, Chmarzyński and Buszewski, 2000)
Moisture content	40-70 % (varies with the method used)	(Fürhacker and Haberl, 1995; Vanegas-Blandón *et al.*, 2007; Malińska and Zabochnicka-Świątek, 2013)
C/N ratio	20-35	(Parvaresh, Shahmansouri and Alidadi, 2004; Malińska and Zabochnicka-Świątek, 2013)
Air filled porosity	30-60%	(Malińska and Zabochnicka-Świątek, 2013; Zhou *et al.*, 2014)
Time	< 4 weeks (composting) < 6 months (ripening)	(Kosobucki, Chmarzyński and Buszewski, 2000)

If the sewage sludge fails to meet the optimal conditions, many problems can occur. When the oxygen level becomes lower than 5% by volume, an anaerobic condition will exist and the decomposition will produce unpleasant odors due to the emission of gasses like NH3, aldehydes, and H2S. Hygienic stabilization may also not happen in anaerobic environments as a result of low digestion temperature in the composting pile (Sweeten et al., 2014). Since, the thermophilic temperature ($50-71$ ℃) is essential to kill pathogens (Fürhacker and Haberl, 1995; Wong and Fang, 2000), at anaerobic conditions pathogens may not be destroyed as in the aerobic conditions (Parr, Epstein and Willson, 1978). Therefore, it is essential to maintain optimal thermal conditions when the sewage sludge is composted. However, according to Table 2, it can be seen that the sewage sludge does not meet the optimal conditions for composting under normal circumstances. The carbon to nitrogen (C/N) ratio of raw sludge is too low and the moisture content (MC) is too high for best compostable conditions (see Tables 1 and 2).

Table 2: Compositions of sewage sludge

Parameters	MC (%)	Volatile solid (%)	pH	C/N	Organic Matter %	Air-filled porosity %
Sewage sludge	70-85	50-70	7-9	Lower than 10 (6-8)	50-60	10-20

It was reported that some materials known as bulking agents can improve the conditions for composting sewage sludge. Different co-composting methods were investigated by researchers to optimize the composting process (Sikora et al., 1981; Kosobucki, Chmarzyński, and Buszewski, 2000; Sweeten and Auvermann, 2008)

2.1 Indore composting

Sir Albert Howard is considered the pioneer of modern composting technology. Indore method of composting developed in Indore between 1924 and 1931, was reported as the start of composting research (Fitzpatrick, Worden and Vendrame, 2005). This method required 4-6 months of composting time depending on the type of organic waste (Fitzpatrick et al., 2005; Parr et al., 1978). In this method, the pile is manually turned periodically throughout the processing time, and only natural aeration is allowed (Parr, Epstein, and Willson, 1978). However, according to Gao et al. (2010), it is essential to maintain a desired level of aeration rate in the composting pile for better performance of microbial activities. Otherwise, the microbial activities will reduce and the performance will gradually reduce over time. Since this method does not use any mechanical aeration, it takes a longer digestion time compared to recently developed composting methods. Indore method is considered as a combination of aerobic and anaerobic processes (Parr, Epstein, and Willson, 1978).

2.2 Windrow method

The windrow method can be used to compost the dewatered sludge (Parr, Epstein, and Willson, 1978). Nowadays, it is the most common method of composting sewage sludge (Parvaresh, Shahmansouri, and Alidadi, 2004). Windrow is an open composting technology that requires minimal attention (Fitzpatrick, Worden, and Vendrame, 2005; Sweeten and Auvermann, 2008). This method is not suitable for composting raw sludge, since high moisture content makes the composting pile a low porous (Higgins *et al.*, 1986; Wu *et al.*, 2015). Therefore, aeration either naturally or mechanically is possible until the moisture content is reduced (Sweeten and Auvermann, 2008). In the forced aeration method, compressors and air blowers are used to supply air through a pipe network. Initially, at least 5 -10 scfm of air per cubic yard of compost should be supplied but this can be reduced with time (Sweeten and Auvermann, 2008).

During the process of the windrow method, the optimal value of moisture content should be maintained around 65-70%. If the moisture content falls below 55%, water should be added before turning (Fürhacker and Haberl, 1995). This is necessary to ensure the efficient activities of the microbial community. The windrows should be turned periodically for aeration and mixing (Sweeten and Auvermann, 2008). When turning, the temperature fluctuates (Lu *et al.*, 2020), but the temperature should be kept above 55℃ (thermophilic region) for a minimum of 15 days for better progress of thermophilic activities (CCME, 2005). Usually, a window pile takes about one month to complete the composting process (Sweeten and Auvermann, 2008).

2.3 Aerated binned composting method

The aerated binned composting method is one of the In-vessel methods. In this method also aeration is done mechanically or naturally (Misra, Roy, and Hiraoka, 2003). As in previous methods, compressors and blowers are used to aerate piles mechanically. The aerated bin composting method can be categorized into two methods, such as batch-operated systems and continuous flow-operated systems. In batch batch-operated system, composting materials are transferred into the next bin periodically in the process (Misra, Roy, and Hiraoka, 2003; Sweeten and Auvermann, 2008). In a continuously operated system, during one month of composting more stabilized-humus-like compost is produced (Sweeten and Auvermann, 2008).

2.4 The Beltsville Aerated Pile Method

Beltsville Aerated Pile Method can be used to compost raw sewage sludge (Parr, Epstein, and Willson, 1978). In this method, sludge is mixed with bulking agents and remains stationary in a pile for 21 days. The composting period can be extended for 3 weeks to overcome the interruptions that occur due to low temperatures and other obstacles (Willson *et al.*, 1980). Woodchips are the most common bulking agent used for this method. The purpose of adding bulking agents is to reduce the moisture content to an optimal value and improve the structure of the pile to be aerated. This increases the biosolids of sludge by around 22% to 40% by removing excess water (Parr, Epstein, and Willson, 1978). For this method, continuous aeration should be applied after mixing with a bulking agent. Blowers are used to draw air into piles forcedly. The average aeration rate is 8-10 scfm per dry ton of sludge (Sweeten and Auvermann, 2008). It keeps a uniform temperature distribution throughout the composting pile (Parr, Epstein, and Willson, 1978). This provides an oxygen level of around 5-15% in the pile ensuring the rapid degradation of organic matter and removing excess moisture. These thermophilic activities increase the temperature in the thermophilic region which is above 55℃ and leads to pathogen destruction (Parr, Epstein, and Willson, 1978; Willson *et al.*, 1980). This condition needs to be maintained for at least 3 days (CCME, 2005).

This method is slightly different from the windrow's method. This method can destroy pathogens more than the windrow method. It can be used to compost either digested sludge or raw sludge. Also, it is a more cost-effective and more flexible method than the windrow method(Parr, Epstein, and Willson, 1978).

3. Bulking Agents

Bulking agents, which are used to upgrade the composting process of sewage sludge, can be categorized into two parts, inorganic bulking agents and organic bulking agents (Wu *et al.*, 2015). Some of the organic bulking agents are pinewood, rice straw, rice hull, woodchips, sawdust, sunflower stalk, wood shaving, wheat straw, etc (Parvaresh, Shahmansouri and Alidadi, 2004; Vanegas-Blandón *et al.*, 2007; Uçaroğlu and Alkan, 2016; Nguyen and Shima, 2018; Liu *et al.*, 2020). Some of the inorganic bulking agents are pumice, recyclable plastic, shredded rubber, zeolite, etc (Higgins *et al.*, 1986; Zorpas and Loizidou, 2008; Wang *et al.*, 2013; Wu *et al.*, 2015). Organic bulking agents are biodegradable materials which utilized along with the sewage sludge during the composting process (Wu *et al.*, 2015). Therefore, they are not recyclable as it is because they cannot be screened after the composting process (Wang *et al.*, 2013). Inorganic bulking agents are the opposite of organic bulking agents. They can be separated easily after the process and reused. Also, they contain less organic matter compared to organic bulking agents (Wang *et al.*, 2013).

4. Results and Discussion

The temperature, CO_2 emission rate, NH_3 emission rate, the composition of organic matter, and pH of the final compost are the main indicators that ensure the stability of the final compost product (Wang, Mao, and Li, 2017; Nguyen and Shima, 2018; Liu *et al.*, 2020). The results obtained for these parameters in the published literature are summarized in Table 3.

4.1 Temperature

The temperature of the composting pile is an important parameter that ensures the maturity of compost (Nguyen and Shima, 2018). Due to the biodegradation of sludge by microorganisms, the temperature of the pile increases and sanitizes the compost mixture by the destruction of pathogenic microorganisms (Wong and Fang, 2000; Uçaroğlu and Alkan, 2016). Yañez et al. (2009) identified three phases of composting according to the temperature fluctuation during the process namely mesophilic, thermophilic, and maturation. In the mesophilic phase, the temperature remains below 40℃ and easily degradable organic matter in the sludge (Yañez, Alonso ,and Díaz, 2009; Zhou *et al.*, 2014). Then the heat released from the thermophilic phase leads to thermophilic phase which has a temperature above 40℃. In the thermophilic phase, the temperature decreases to around 40℃ (Yañez, Alonso, and Díaz, 2009). To kill pathogens, the thermophilic phase should last for several days according to the method used (CCME, 2005).

It can be seen in Table 3 that all the composting mixtures with bulking agents except for ceramist have reached a maximum temperature within the thermophilic region. In mixtures with ceramsite, the bulking agent stayed below 20℃. Therefore, it can be concluded that ceramsite is not a suitable bulking agent for sewage sludge composting. Woodchip sand recyclable plastic has been reported with maximum temperatures reaching above 70℃. Particle size distribution of bulking agents also plays a vital role. For example, when the ratio of small-size recyclable plastic content is low, the porosity of the composting mixture lowers and minimizes the air transfer through the composting pile. In such systems, the thermophilic region would last for a longer duration (Zhou *et al.*, 2014).

Zhou et al. (2014) recommended recyclable plastic with sizes in the range of 50 mm (RPBA50) with a ratio of 1:2 as the most suitable bulking agent. For woodchips, Nguyen & Shima et al. (2018) reported that the temperature could go up to 70℃, bot least form minimum days required for pathogen destruction. This happened because of the lack of insulation and low ambient temperatures. In a similar research, Lu et al. (2020) reported the woodchip in the ratio of 3:1 and 4:1 with comestible matter obtained a maximum temperature around67℃ and lasted in the thermophilic phase for a suitable period. However, an increased amount of woodchip results in a decrease in the temperature due to the excessively increased porosity.

4.2 NH_3 Emission

The rate of NH_3 emission is another parameter that ensures the quality of compost (Liu *et al.*, 2020). During the composting process total nitrogen content of sewage sludge can be reduced due to ammonia emission which results in decreasing the nutritional value of the final compost (Li *et al.*, 2013; Meng *et al.*, 2021). Also, it causes air pollution by producing odorous gasses (Li *et al.*, 2013). Therefore, NH_3 emissions should be minimized during the composting process for good-quality compost (Liu *et al.*, 2020).

The highest NH_3 emission of different experiments shown in Table 3 is around 1100 mg/kg/day from the experiments with sawdust as a bulking agent without carbon amendment. Sawdust even with carbon amendments such as glucose sucrose, straw powder produced more NH_3 than using other bulking agents. According to Table 3, considerably low NH_3 emissions can be seen in composting experiments done using pumice. Wu et al. (2015), reported that large degradation of organic matter results in reducing the NH_3 emission by assimilating them to nitrogen in the compost. Since pumice promotes considerable degradation of organic matter, it minimizes the NH_3 emission (Wu *et al.*, 2015). Modified pinewood also contributes to a low NH_3 emission as pumice, though unmodified pinewood shows considerably high NH_3 emission as shown in Table 3. The reason for that is that when treating pinewood with acid to make modified pinewood before the composting process, the carbonized layer is produced on the surface of the pinewood sample. This carbonized layer can absorb more NH_3. Therefore, NH_3 emission would be reduced (Liu *et al.*, 2020). Therefore, by analyzing the data, it can be stated that pumice and modified pinewood are promising bulking agents that can reduce the NH_3 emission. Carbon amendments can reduce the NH_3 emission rather than using fresh bulking agents.

4.3 CO_2 Emission and Organic Matter Change

CO_2 emission is another factor that reflects the stability of the final compost (Meng *et al.*, 2021). When degrading organic matter by microorganisms, CO_2 gas is released. Therefore, the rate of CO_2 emission is an indication of the degradation of organic matter (Wu *et al.*, 2015; Meng *et al.*, 2021). As shown in Table 3, the final organic matter percentage in the process decreases with the increase of CO_2 emission in the experiments that used different bulking agents. This shows the reflection of CO_2 emission to organic matter change. CO_2 emission rapidly increases during the thermophilic phase due to an increase in microbial activities and after the thermophilic phase CO_2 emission gradually decreases (Wu *et al.*, 2015).

According to Table 3, the maximum rate of CO_2 emission can be seen in the experiment with wood shaving and pine leaves as bulking agents. This happens because it increases the respiration of microbes and accelerates the degradation (Vanegas-Blandón *et al.*, 2007). Other than that, pumice with or without carbon amendments promotes considerably high CO_2 emissions. As shown in Table 3, it can be seen that adding carbon amendment to pumice increases biodegradation and releases a higher amount of CO_2 than using fresh pumice as a bulking agent. Also adding cellulose as a carbon source could not increase biodegradation than other carbon sources because due to complex macromolecular structure, it is too hard to utilize by microorganisms (Meng *et al.*, 2021). Therefore, its CO_2 emission rate is low compared to others. Hence, analyzing the data given in Table 3, glucose can be considered as the best carbon amendment among others, because it releases considerable CO_2 gas due to simple microstructure (Meng *et al.*, 2021).

Table 3: Physiochemical characteristics of composting mixtures

Bulking agent	**time (day)**	**Max Temp. ℃**	**NH_3 emission (peak) mg/kg/d**	**CO_2 emission (peak) mg/kg/d**	**OM change %**	**References**
Modified Pinewood	16	62.5	179.22		63.23-50.42	(Liu *et al.*, 2020)
Un – modified Pinewood	16	61.0	597.86		63.23-53.29	
Fresh Pumice	26	51	~320	~150		(Wu *et al.*, 2015)
	32		160.35	134.75	61.3-41	(Meng *et al.*, 2021)
Pumice-Sucrose	26		~300			(Wu *et al.*, 2015)
	32		92.9	244.8	67.3-38.4	(Meng *et al.*, 2021)
Pumice-Glucose	32		98.75	268.15	66-37.6	(Meng *et al.*, 2021)
Pumice-Reused	26	53	~240	~200		(Wu *et al.*, 2015)
Pumice-Cellulose	32		145.3	165.3	66-41.2	(Meng *et al.*, 2021)
Pumice-Starch	32		119.75	200.6	65.3-40.1	(Meng *et al.*, 2021)
Woodchip	57	74.8			50.2 loss	(Nguyen and Shima, 2018)
	44	67				(Lu *et al.*, 2020)
Ceramsite	44	<20				(Lu *et al.*, 2020)
Wood shaving-Pine leaves	73	~65		~3000		(Vanegas-Blandón *et al.*, 2007)

Fresh Sawdust	22	<60	~1100			(Li *et al.*, 2013)
Sawdust-Glucose	22	<60	~700			(Li *et al.*, 2013)
Sawdust-Straw powder	22	<60	~900			(Li *et al.*, 2013)
Sawdust-Glucose+ Straw powder	22	62	~650			(Li *et al.*, 2013)
RPBA35	16	65-73				(Zhou *et al.*, 2014)
RPBA50	16	73				(Zhou *et al.*, 2014)

5. Conclusion

Sewage sludge is a biodegradable residue that contains a high amount of organic matter that can be treated by biological methods. Sludge composting plays a major role in this concern. However, the high moisture content and low C/N ratio make the sewage sludge difficult to compost as it is. Since the sewage sludge fails to meet its optimal conditions for composting there is a need for an additional material, called bulking agents which can upgrade the compostability of sewage sludge. There are several methods for composting sewage sludge with the help of bulking agents. Among them, Indore composting which uses natural aeration takes too long a time to compost (around 4-6 months) compared to other methods due to its lower rate of microbial activities. Others like the Windrow method, Beltsville aerated pile method, and aerated binned composting method use mechanical or forced aeration, therefore they take less time to compost the sewage sludge.

When considering the effect of bulking agents for composting, a few indicators ensure the maturity and stability of the compost. Temperature, CO_2 emission, NH_3 emission, and organic matter percentage are some of them. According to the analysis, woodchips and recyclable plastic can be selected as the best bulking agents. These materials allow the temperature of the composting pile to reach conditions suitable for thermophilic microorganisms and hold for sufficient periods for destroying pathogens. Adding more than the optimum levels of bulking agents results in increasing porosity and lowering temperature. Concerning NH_3 emission, pumice, and modified pinewood can be selected as suitable agents. The CO_2 emission rate is an indication of the biodegradation of organic matter. When considering CO_2 emission, wood shaving, and pine leaves can be selected as more suitable agents. The addition of an external carbon source to the composting pile together with a bulking agent can increase the performance of composting.

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MODELLING SIMULATION OF ELECTROCHEMICAL CELLS FOR WATER TREATMENT

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Abstract: Electrochemical technologies are a promising alternative for the treatment of water and wastewater containing various types of pollutants. Different electrochemical treatment methods are used for water treatment to introduce new economically efficient solutions to water and wastewater treatment challenges. To evaluate the performance of electrochemical methods, reactor behavior can be studied by varying physical parameters and operating conditions of the electrochemical reactors. Most of the literature is based on experimental studies to evaluate the reactor behavior. Although computational modeling is an effective method for a better understanding of reactors, scaling up of reactors, etc. it is lacking in the literature. Therefore, this research was focused on developing computational models to understand the reaction behavior of disinfection of E. coli and E. faecalis in ballast water through the electrochemical oxidation process based on data published in previous research studies. Aquasim software (Version 2.1g) was used to develop the reaction models. The software helps to develop the system from initial modeling to advanced simulations. Final concentration profiles and reaction rate constants were derived. The reaction rate constant was reduced with the increase of the initial concentration of the considered bacteria for the developed reactor. The reaction rate constant of the pilot scale reactor did not follow the trend indicating the scale-up effect.

Keywords: Electrochemical Oxidation; Reaction Modelling; Concentration Profile; Reaction Rate Constant

1. Introduction

Collapsible soils, known as metastable soils, are unsaturated soil types that experience significant volume alteration when they become saturated. The change can occur with or without the application of additional load. Large regions in eastern Canada, the United States, eastern Europe, China, and Europe are significantly affected by the hazards posed by collapsible soils. In the Sri Lankan context, collapsible soils can be found in some areas of the Matale district (De Zoysa et al, 2022). Considering the characteristics described in the literature, collapsible soils are soils that remain stable in unsaturated conditions but display significant volume changes with saturation.

Collapsible soils present significant challenges during design, construction, and service. Differential settlements caused by collapsible soils cause considerable structural damage to buildings. In addition to problems related to buildings, rough and bumpy surfaces are developed on roads due to the presence of collapsible soils. Figure 1 shows a wall that has cracked due to the presence of collapsible soil.

Figure 1: Cracked wall due to collapsible soil (Culshaw and Jefferson, 2018).

Collapsible soils have been widely studied for decades resulting in broad literature. Jennings and Knight, (1975) defined the collapse potential (CP) as the collapse strain due to wetting at an applied pressure of 200 kPa and described a laboratory test to compute the collapse potential: An undisturbed soil specimen is taken at its natural water content in a consolidation ring. Step loads are applied to the specimen up to a pressure level of 200 kPa. At that pressure, the specimen is flooded for saturation and left for 24 hours. This test defines the void ratios e1 and e2 before and after flooding. The collapse potential under one-dimensional conditions can subsequently be calculated using Equation (1).

$$CP = \frac{e_1 - e_2}{1 + e_0} \qquad (1)$$

Where,
e_1 – Void ratio before flooding
e_2 – Void ratio after flooding
e_0 – Natural void ratio of the soil

Numerous studies have been conducted to investigate the impact of various geotechnical parameters on the collapse potential. Basma and Tuncer (1992) investigated the effect of soil type, compaction water content, initial dry unit weight, and applied pressure at wetting on collapse potential. It was concluded that collapse potential decreases with an increase in the difference between the sand and clay percentages, compaction water content, and initial dry unit weight, while it increases with pressure at wetting. Likewise, a higher Coefficient of Uniformity (Cu) indicates a higher collapse potential. Klukanova and Frankovaska (1995) suggested threshold values to define the collapse potential: silt content greater than 60%, clay content less than 15%, degree of saturation less than 60%, liquid limit below 32%, porosity greater than 40%, and natural water content less than 13%. Mellors (1995) investigated the influence of the clay fraction within the soil on the collapse process and concluded that the collapse phenomenon occurs through micro-shearing at the intergranular contacts and is influenced by the clay component in the soil. Clevenger (1958) conducted extensive laboratory studies to investigate the collapse behavior of loess and proposed an empirical relationship in terms of dry unit weight. Furthermore, Feda (1964) proposed an empirical equation to calculate collapse potential and identified plastic limit and plasticity index as the most influential parameters.

Numerous studies have suggested various indirect methods to estimate the collapse potential that correlate with other index properties (Handy, (1973); Holtz & Hilf, (1961); Ashour et al., (2020)).

The functional relationship between various soil parameters and collapse potential is not well established and a more reliable interrelationship is still a matter of speculation. Therefore, the objectives of this study are to develop relationships between the collapse potential of a soil and the most influential parameters and to predict the collapsibility of soil reliably even with a limited number of parameters.

2. Methodology

Artificial Neural Networks, a branch of artificial intelligence, aim to simulate the functioning of the human brain and nervous system. In contrast to conventional empirical and statistical methods that require pre-existing knowledge about the relationships within the data, ANNs can discover patterns and connections without prior information about the nature of these relationships. The Multi-Layer Perceptron Artificial Neural Network, renowned for its ability to accurately approximate continuous functions (Hornik et al., 1989), was utilized in this study to investigate the relationship between collapse potential and several crucial parameters.

2.1 Model Inputs

In this study, coefficient of uniformity, initial water content, initial dry density, sand content, clay content, Liquid Limit, Plasticity Index, and applied pressure at wetting were considered as different initial conditions for the oedometer tests. Altogether, 327 data points obtained from the literature were used as the database for the development of the ANN model.

2.2 Data Preprocessing

2.2.1 Outlier removal

The first step of the process was to identify the outliers in the data set. The method proposed by Hampel (1971) was adopted to detect and remove the outliers based on Mean and Mean Absolute Deviation (MAD). Threshold values based on the Median and MAD can be defined as,

$$MAD = median(|x_i - median(x)|) \quad (2)$$
$$Threshold = (median(x) \pm 3 \times MAD) \quad (3)$$

Each variable was separately considered, and the outliers were identified concerning each variable. If one data point is identified as an outlier concerning more than two variables, then only it is considered as an outlier (Gunasekara et al., 2020).

2.2.2 Data normalisation

Differences in the scales across input variables may increase the complex behavior of the ANN model and may lead to inaccurate predictions. Therefore, the input and output variables were generalized between 0 and 1. A value can be normalized by using Equation (4), which is as follows.

$$\mathrm{MAD} = (\mathrm{x} - x_{min})/(x_{max} - x_{min}) \tag{4}$$

x - any data point

x_{min} – Minimum value of the data set

x_{max} – Maximum value of the data set

2.2.3 Data Division

Data division in Artificial Neural Network (ANN) refers to the process of splitting a data set into separate subsets for training, validation, and testing. The main objective of the data division is to prevent overfitting problems in the ANN model. In this analysis, 80% of the oedometer test results were used for calibration purposes and 20% of the oedometer test results were used for validation of the ANN model as adopted by Shahin et al. (2004). Furthermore, 70% of the calibration data was used for training purposes and the remaining 30% was used for testing purposes.

2.3 Model Architecture and Learning Process

Model architecture refers to the overall structure and arrangement of the network such as the number of neurons in each layer, the number of layers in the model, and the connection between nodes in each layer. The design of suitable architecture is the most important and the most difficult part of the ANN model development process (Maier and Dandy, 1996). The architecture of the ANN model is highly problem-dependent, and consequently, it has a significant impact on the predicted collapse potential. Furthermore, depending on the complexity of the problem, multiple hidden layers may be required.

Multi-Layer Perceptron is the most used architecture in the geotechnical engineering context (Shahin et al., 2008) which was adopted in this study. Multi-layer Perceptron processing elements called nodes or neurons are arranged in layers; consisting of an input layer, an output layer, and one or more intermediate layers called hidden layers. In MLP, each node in a layer is connected to every node in the following layer via weighted connections and Figure 1 shows the architecture of MLP.

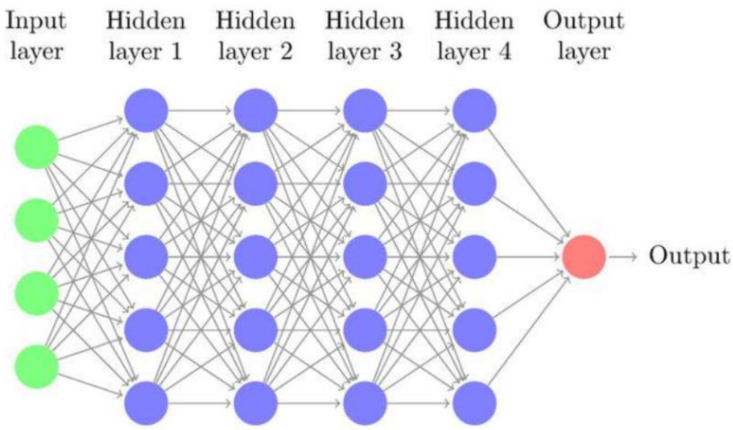

Figure 2: Multi-Layer Perceptron Architecture.
(Hutson, 2022)

There is no unified approach to determine the number of neurons in each layer and the number of layers. Optimal network geometry is highly problem-dependent and ANN with a single hidden layer was the starting point. Then, a trial-and-error method was followed with varying numbers of nodes and layers. Based on the performance, the optimal architecture was determined. Thus, the overall architecture of the ANN model consisted of 8 inputs and featured 2 hidden layers, one with 9 neurons and the other with 8 neurons, resulting in a structure of 8-9-8-1.

As shown in Figure 3, at each processing element (neuron), weighted inputs are summed up, and bias is added (Ij). In the next stage, the combined summation is passed through an activation function which produces the output of the neuron (yj).

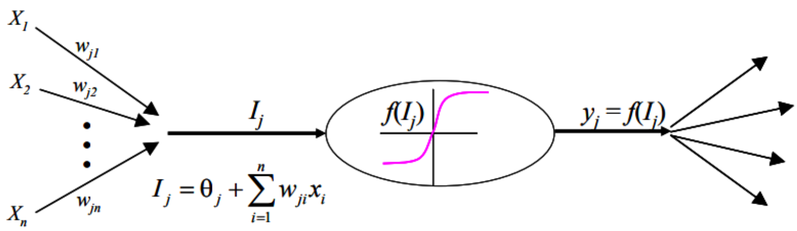

Figure 3: Operation inside a neuron.
(Shahin et al., 2008)

Prediction is produced in the final layer and error is calculated concerning the known output. Then this error is back propagated, weights are readjusted, and the process is continued until it produces the output that has the smallest possible error. The process by which the weights are recalculated is called the "learning process".

2.4 Activation Functions

The activation function is a mathematical function applied to the output of a neuron or a layer of neurons. It introduces non-linearity into the network, enabling it to learn complex patterns and make more powerful predictions.

Activation functions map any real number into the domain of -1 to 1 or 0 to 1. Since collapse potential lies between 0 and 1, an activation function with the domain of 0 to 1 should be selected for the output layer. For the hidden layers, there is no such restriction. Therefore, this study utilized the "ReLU" function for the hidden layers 1 and 2. For the output layer, the "sigmoid function" was selected because the output should be in the range of 0 and 1.

2.5 Performance Criteria

The performance of the ANN model was assessed in terms of Coefficient of correlation (R2), Root Mean Square Error (RMSE), and Mean Absolute Error (MAE). R2, RMSE, and MAE were examined in the training, testing, and validation stages. Higher values of R2 and lower values of RMSE and MAE indicate a model with better performance.

2.6 Stopping Criteria

Obtaining higher performance criteria does not always ensure a better generalized ANN network. It is possible to overtrain the network and stopping criteria must be introduced to avoid the overfitting problem. The Stopping criterion for the ANN was defined using the "Early Stopping" callback in the Keras library. In this criterion, training of the ANN model is stopped if the loss doesn't improve for the specified number of epochs. The minimum desired improvement in the loss (minimum delta) and the optimum number of epochs (patience) need to be specified. In this study, the minimum delta was set to 0.001 and patience was selected as 20.

2.7 Sensitivity Analysis

The determination of the relative importance of each parameter is crucial for maximizing the utilization of Artificial Neural Networks. Sensitivity analysis methods that are based on the connection weight cannot be utilized for the ANNs with multiple hidden layers and therefore, other sensitivity analysis methods need to be adopted. In this study, the Cosine Amplitude Method (CAM) (Yang and Zhang (1997)) was utilized to determine the importance of each parameter on the collapse potential.

Using this approach, all the data points were defined as an array as shown in Equation (5) (Jong and Lee (2004); Khandelwal and Singh (2006)).

$$X = \{x_1, x_2, x_3, \ldots, x_i, \ldots x_n\} \tag{5}$$

Where, each element X_i is a vector of the length m as shown in Equation (6).

$$x_i = \{x_{i1}, x_{i2}, x_{i3}, \ldots, x_{im}\} \tag{6}$$

Each data point can be fully described by m-coordinates. The strength of the relationship between x_i and x_j can be expressed by Equation (7).

$$r_{ij} = \frac{\Sigma_{k=1}^{m} x_{ik} x_{jk}}{\sqrt{\Sigma_{k=1}^{m} x_{ik}^2 \; \Sigma_{k=1}^{m} x_{jk}^2}} \tag{7}$$

3. Results

3.1 Sensitivity Analysis

The results of the sensitivity analysis are presented in Figure 4, and the Liquid Limit was identified as the most influential parameter. Following closely are the plasticity index, clay content and the coefficient of uniformity. Furthermore, sand content and initial water content have the least contribution to the collapse potential of soil.

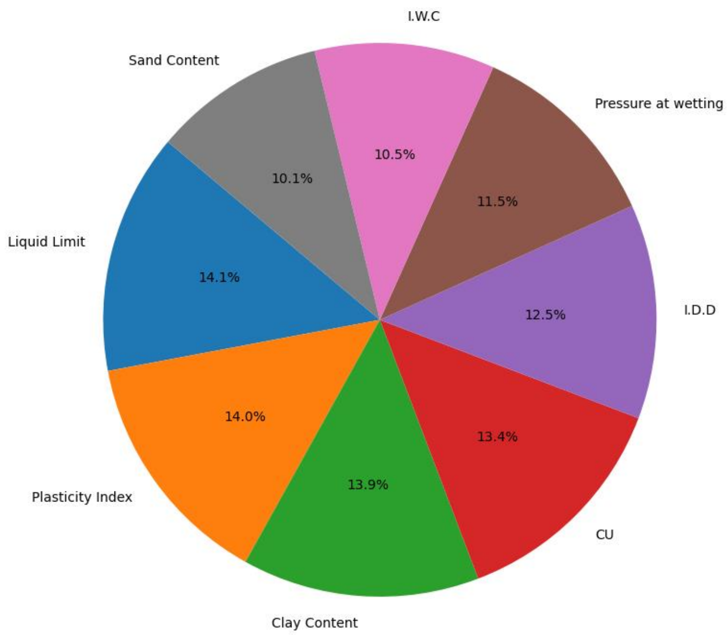

Figure 4: Sensitivity of input parameters on collapse potential.

Sand content, Initial water content, and pressure at wetting were identified as the least important parameters on the collapse potential having an importance value of 0.5680, 0.5922, and 0.6489 respectively. Three separate ANNs were developed without these parameters to predict the collapse potential with compromised accuracy.

3.2 Model 1 (With all 8 parameters)

For the first relationship, a model was trained with 8 input parameters. Table 1 shows the R2, MSE, and MAE for training, testing, and validation stages. It shows that training, testing, and validation data sets correlate well with experimental results with an overall R2 of 0.9081. Overall MSE and MAE of the model were 0.0004 and 0.0159 respectively.

Table 1: Performance of the ANN model with 8 input parameters

	Training	**Testing**	**Validation**	**Overall**
Coefficient of Determination (R^2)	0.9235	0.8808	0.8727	0.9080
Mean Squared Error (MSE)	0.0004	0.0005	0.0005	0.0004
Mean Absolute Error (MAE)	0.0150	0.0169	0.0169	0.0159

3.3 Model 2 (7 Parameters: without Sand content as a parameter)

For the second relationship, sand content was excluded, and the model was trained with the 7 most influential input parameters; coefficient of uniformity, initial water content, initial dry density, clay content, Liquid Limit (LL), Plasticity Index (PI), applied pressure at wetting.
Table 2 shows the R^2, MSE, and MAE for training, testing, and validation stages. As anticipated, this second ANN model, exhibited a slight reduction in R^2 during both the training and validation phases compared to the first model with 8 input parameters.

Table 2: Performance of the ANN model with 7 input parameters

	Training	**Testing**	**Validation**	**Overall**
Coefficient of Determination (R^2)	0.9088	0.8886	0.8604	0.8991
Mean Squared Error (MSE)	0.0005	0.0005	0.0006	0.0005
Mean Absolute Error (MAE)	0.0175	0.0180	0.0183	0.0178

3.4 Model 3 (6 Parameters: without Sand and Initial Water Content as parameters)

For the third relationship, the least two influential parameters, sand content and initial water content were excluded, and the model was trained with 6 input parameters: coefficient of uniformity, initial dry density, clay content, Liquid Limit (LL), Plasticity Index (PI), and applied pressure at wetting.

Table 3 shows the R^2, MSE, and MAE for training, testing, and validation stages. This third ANN model, which was fed by 6 input parameters, exhibited a further reduction in R^2 especially in the testing stage ($R^2 = 0.6996$) compared to the R^2 of the first and second models in the testing stage. This can be expected due to the limited number of input parameters.

Table 3: Performance of the ANN model with 6 input parameters

	Training	Testing	Validation	Overall
Coefficient of Determination (R^2)	0.8305	0.6996	0.8064	0.8028
Mean Squared Error (MSE)	0.0009	0.0014	0.0008	0.0010
Mean Absolute Error (MAE)	0.0227	0.0263	0.0211	0.0232

3.5Model 4 (5 Parameters: without Sand content, Initial Water Content, and Pressure at wetting as parameters)

For the fourth relationship, sand content, initial water content, and pressure at wetting were excluded and the model was trained with 5 input parameters: coefficient of uniformity, initial dry density, clay content, Liquid Limit (LL), and Plasticity Index (PI).

Table 4 shows the R^2, MSE, and MAE for training, testing, and validation stages. This fourth ANN model, which was fed by 5 input parameters, exhibited a slight reduction in R^2 during both the training, testing, and validation phases compared to the previous ANN model.

Table 4: Performance of the ANN model with 5 input parameters

	Training	Testing	Validation	Overall
Coefficient of Determination (R^2)	0.7876	0.6806	0.7888	0.7706
Mean Squared Error (MSE)	0.0011	0.0014	0.0009	0.0011
Mean Absolute Error (MAE)	0.0260	0.0270	0.0220	0.0254

4. Conclusions

In this study, an Artificial Neural Network (ANN) was implemented using Python programming language to predict the collapse potential of soils. Four different ANN models were developed with several input parameters varying from 5 to 8 most influential parameters to predict the collapse potential of soils with increasing accuracy. The feedforward backpropagation method was employed to train the model, and the optimal model architecture was determined through a trial-and-error approach, resulting in a structure of 8-9-8-1. Furthermore, based on the Cosine Amplitude Method, Liquid Limit was identified as the most influential parameter on the collapse potential, while sand content was found to be the least contributing factor. The ANN model's predictions are in good agreement with the experimental results.

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A CRITICAL REVIEW ON MICROPLASTICS ABUNDANCE IN MUNICIPAL WASTEWATER

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Abstract: Microplastics has become one of the main causes of global water contamination. Wastewater treatment plants (WWTPs) have a dual function in this problem since they are both barriers to preventing the spread of Microplastics and sources of Microplastics in freshwater ecosystems. This is primarily because typical WWTPs are not built with the removal of Microplastics as their primary goal in mind. Since typical WWTPs treat most municipal wastewater, it is essential to concentrate on determining the prevalence of Microplastics in this setting. The objective of this literature review is to obtain an understanding of the opportunities and difficulties related to microplastic (MP) removal within the framework of traditional wastewater treatment. In this extensive literature study, firstly, the characteristics of Microplastics found in municipal wastewater were investigated and the effectiveness of various WWTPs in eliminating these pollutants was evaluated. Furthermore, this study has explored MP forms, dimensions, and abundance at primary, secondary, and tertiary treatment phases within WWTPs. By rigorous inspection and analysis, it is desired to identify the most prevalent types and size ranges of Microplastics found in municipal wastewater treatment systems. This review has shed light on the current condition of MP contamination in municipal wastewater and the effectiveness of existing WWTPs in resolving this issue by compiling and assessing the results from a variety of studies. The outcomes of this study will guide future initiatives to reduce the release of Microplastics into freshwater settings, protecting aquatic ecosystems and public health. They will also help identify possible technologies for improving MP removal.

Keywords: Microplastic; Municipal; Wastewater; Water treatment

1. Introduction

Plastics or in other words, synthetic polymers can be identified as one of the most used materials in the world (Delerue-Matos, 2022). Plastics have been produced and used more and more since their first invention because of a variety of economically advantageous attributes, including durability, lightness, ease of formability, and insulating qualities (Akdemir and Gedik, 2023). With the increment of plastic usage, advantageous characteristics, and unfavorable characteristics have also become more prevalent in the present time. While they can survive in the environment for a long time without decomposing due to their resilience, low recycling rates and an accumulation in the ecosystem have made them one of the most significant pollutant causes of the century (Akdemir and Gedik, 2023). An estimated 360 million tons of plastic were produced globally in 2019, with China producing 31% of the total, followed by North America with 19% and Europe with 16% (Zhang *et al.*, 2022). Each year, 12 million tons of illegally dumped plastic pollution are predicted to make their way into the ocean (Akdemir and Gedik, 2023). It is estimated that plastic production will double over the next 20 years if the present growth rate continues (Üstün, Bozdaş, and Can, 2022).

Depending on the number of microplastics arriving from residence waste, the population density made possible by human activities within the service region, and the efficacy of treatment, WWTPs release varying amounts of MP into the aquatic environment. microplastics represent a recently acknowledged class of plastic contaminants, encompassing plastic particles with dimensions ranging from 5 millimeters to 1 nanometer in size (Perren, Wojtasik and Cai, 2018; Long *et al.*, 2019; Ma *et al.*, 2019; Yuan *et al.*, 2019; Ziajahromi *et al.*, 2021; Akdemir and Gedik, 2023). Microplastics can be divided into primary and secondary particles to help identify their sources and find a way to prevent them from entering the environment (Padervand *et al.*, 2020a; Delerue-Matos, 2022; Setiadewi *et al.*, 2023). Materials including resin pellets, micrometer pellets, and personal care products (facial cleansers, face wash, soaps, and toothpaste) are primary microplastics, while secondary microplastics are created when raw plastic particles are degraded by physical, chemical, and biological processes in the environment (Padervand *et al.*, 2020a; Delerue-Matos, 2022). Primary microplastics are at least less than 10 μm in size, and their average size is between 150 and 330 μm (Azizi *et al.*, 2022). Hence, the sources of microplastics encompass a diverse array of origins, ranging from everyday personal care products and synthetic clothing to industrial processes like air-blasting facilities and drilling fluids within the gas-oil industries (Padervand *et al.*, 2020b; Ahmed *et al.*, 2021). These MP particles also emerge from the production cycle itself, including the release of raw plastic powders from plastic manufacturing industries, discarded plastic items, and effluents discharged from wastewater treatment plants and household sewage systems (Ahmed *et al.*, 2021). In the methods of MP transportation, wind, and oceans can be identified as the major transportation methods (Padervand *et al.*, 2020a). However, their journey is not limited to marine environments alone. Rivers emerge as vital conduits, carrying substantial volumes of plastic particles across considerable distances (Padervand *et al.*, 2020a). Small waterways like stormwater drains could also be an alternative to huge rivers. The amount of information on microplastics in stormwater is currently restricted, though. Domestic sewage is intimately tied to the daily routines of people, seasonal variations, and rainfall patterns, which may have an impact on how many microplastics are present in sewage and stormwater (Zhang *et al.*, 2022).

Municipal WWTPs can be identified as essential facilities that process and treat sewage and wastewater generated by homes, businesses, and industries within a community. These plants employ various treatment methods, including biological and chemical processes, to remove pollutants and contaminants from the wastewater, ensuring that it can be safely returned to the environment or reused, thus protecting public health and the environment. According to Murphy et al., (2016), a network structure of urban pipes allows a significant amount of microplastic particles from the above sources to enter WWTPs. On one hand, the WWTPs act as barriers, but on the other, they also serve as the primary ports of entry for microplastics into the soil and aquatic habitats through the disposal of sludge and the release of effluent (Murphy *et al.*, 2016; Blair, Waldron and Gauchotte-Lindsay, 2019; Xu *et al.*, 2020). In this study, information regarding the abundance of microplastics in WWTPs, removal efficiencies at different stages of the WWTPs, and the characteristics of microplastics are gathered.

Due to reported health issues and environmental problems related to microplastics, it has become an upcoming topic in today's world. According to earlier research studies, microplastics can remain chemically stable in water for thousands of years, causing the marine ecosystem to suffer substantial economic losses. However, the worst part is hazardous organic compounds and heavy metals like zinc, copper, lead, and silver as well as some nanoscale adsorbents like Titanium Oxide can be transported effectively by the absorption ability of microplastics (Ma *et al.*, 2019). Microplastics can absorb polybrominated diphenyl ethers (PBDEs), endocrine-disrupting chemicals (EDCs), pharmaceuticals, and personal care products (PPCPs) in addition to other persistent organic pollutants in aqueous conditions due to their hydrophobic nature (Carr, Liu and Tesoro, 2016). Concentrations of PPCPs, EDCs, and PBDEs, which are found in numerous wastewater samples at parts per trillion could be absorbed and enriched on the surfaces of microplastic particles (Nelson *et al.*, 2011). If fish, aquatic invertebrates, and other species consume the polluted plastic remnants, these hazardous contaminants may eventually find their way into the food chain of an ecosystem, and create health problems (Carr, Liu, and Tesoro, 2016). These factors emphasize the importance of studying the abundance of microplastics in WWTPs and to date, the removal efficiencies for different phases of the wastewater treatment process and the comprehensive summary of the characteristics of microplastics are lacking.

2. Characteristics of microplastics in municipal wastewater

Microplastics in municipal wastewater are abundant and diverse in terms of types, sizes, shapes, and colors. The major types of microplastics identified in wastewater include polyethylene (PE), polypropylene (PP), polyethylene terephthalate, and polystyrene (Yuan *et al.*, 2019; Tadsuwan and Babel, 2022). The size of microplastics in wastewater ranges from smaller than 483.9 μm to <500 μm, with the dominant size being 25-200 μm (Wang *et al.*, 2020). The shape of microplastics in wastewater is mainly in the form of fibers, which are believed to originate from synthetic fibers used in clothing and personal care products (Monira *et al.*, 2023). The primary source of microplastics in municipal wastewater is believed to be from the petrochemical industry, which is responsible for the majority of plastic production. In WWTPs, microplastics can be removed to some extent through various treatment processes, but complete removal is challenging. The fate of microplastics in WWTPs can vary depending on the specific treatment processes employed, with lagoon systems and activated sludge-lagoon systems showing promising microplastic removal capabilities. Information on the microplastic abundance in WWTPs in different locations was gathered here including the details about their types, sizes, shapes, colors, and the removal efficiencies with primary secondary, and tertiary treatment process steps (Table 1).

2.1 Microplastic types

When considering the types of microplastics, synthetic cellulose is mostly found in environmental samples and is typically derived from textiles (Jiang *et al.*, 2022). Polyethylene terephthalate (PET) comes from households and is commonly found in WWTPs (Zhang *et al.*, 2021). Microplastics are the primary ingredient in textiles, synthetic apparel, and food packaging (Mason *et al.*, 2016; Jiang *et al.*, 2022). The second-largest proportion composition of the WWTP influent was made up of Polyurethane (PU) and Polyethylene (PE) (Jiang *et al.*, 2022). PU is widely used in medical equipment and has been found in significant concentrations in the influence of several WWTPs. The main sources of PE microplastics include a variety of plastic goods, including toothpaste, body and face cleansers, and bottles, bags, and cutlery used in food packaging (Carr, Liu, and Tesoro, 2016; Lares *et al.*, 2018; Jiang *et al.*, 2022). As mentioned, several investigations into the type of microplastics found in WWTPs have consistently shown that a variety of polymer types are present at various stages of the treatment process. Acrylic, Polyamide, PE, Polyester, PET, PP, Polystyrene (PS), PU, and Polyvinylchloride (PVC) can be identified as the most common forms of microplastics (Bilgin, Yurtsever and Karadagli, 2020). With average abundances of 45%, 44%, and 26%, respectively, PET, Polyester (PEST), and PE were the predominant polymers (Bilgin, Yurtsever, and Karadagli, 2020). These polymers are widely used in the production of textiles and packaging materials, among other consumer items. The sources of microplastics in wastewater exhibit variability based on the polymer type. For instance, PE in wastewater has been linked to personal care goods such as face scrubs and toothpaste (Alavian Petroody, Hashemi, and van Gestel, 2020). On the other hand, bigger plastic objects are said to erode or degrade due to polymers such as PET, specific types of PE, and PP (Alavian Petroody, Hashemi, and van Gestel, 2020). PP can come from a variety of products, such as building materials, sanitary napkins, medical uses, and thermal clothing (Blair, Waldron, and Gauchotte-Lindsay, 2019).

2.2 Microplastic size

The treatment procedures may be the reason for the different mean particle sizes of microplastics (Jiang *et al.*, 2022). The behavior of microplastics in WWTPs and the ensuing impacts on the environment are significantly influenced by their size. On the one hand, microplastics with varying particle sizes may be removed differently by different treatment units. In WWTPs, Lehtiniemi *et al.*, (2018) stressed the significance of MP size. According to their research, there were between 65.0% and 86.9% of microplastics smaller than 1 mm in influent and between 81.0% and 91.0% in effluent. Smaller particles are more likely to be consumed by aquatic creatures, which could have toxicological effects (Qiao *et al.*, 2019). Microplastics also tend to change from primary to secondary microplastics as they get smaller (Magni *et al.*, 2019). Particles larger than 3 mm can be successfully blocked by primary treatment (Jiang *et al.*, 2020). Smaller microplastics, such as sizes less than 125 μm, are difficult to remove during primary treatment because they can pass past filtration barriers. These smaller microplastics therefore have a higher probability of being discovered in the final effluent (Blair, Waldron, and Gauchotte-Lindsay, 2019; Jiang *et al.*, 2020). Smaller microplastics, particularly those smaller than 0.355 mm, have demonstrated greater removal efficacy in the secondary treatment stage and are frequently present in sludge (Jiang *et al.*, 2020). Smaller microplastics are present in the finished effluent as a result of mechanical abrasion and subsequent size reduction of conspicuous microplastics during wastewater treatment operations (Magni *et al.*, 2019). The distribution of MP sizes in WWTPs is shown by several kinds of studies. The microplastics that have been detected generally have sizes between 102.6 μm and 4887.5 μm, with a median size of 834.7 μm. 42.1% of microplastics are in the range of 100-500 μm, while most microplastics are smaller than 1000 μm (Akdemir and Gedik, 2023). The literature study emphasizes that treatment procedures and the abundance of microplastics with particular particle sizes might cause variations in the size distribution of microplastics between WWTPs. Distinct removal tendencies for microplastics of different sizes may exist among treatment units (Jiang *et al.*, 2020). Changes in the size of microplastics during treatment may also be influenced by mechanical processes, such as stirring in the rotating grit chamber (Liu *et al.*, 2019).

Jiang et al. (2020) demonstrated a reduced removal rate for microplastics with smaller particle sizes. However, because of abrasion, large microplastic particles may get smaller during processing and move on to the next phase (Liu *et al.*, 2019). Physical, chemical, or biological processes were used to break down the primary microplastics into secondary microplastics with progressively smaller particle sizes (Magni *et al.*, 2019).

2.3 Shape of microplastics

Based on the morphologies of microplastics as seen under an optical microscope, microplastics can be categorized into four types: fragments, fibers, films, and granules (Yuan *et al.*, 2022). The fragmentary microplastics may originate from resin-type plastics used in industrial production processes, such as foam boards, insulating boards, and adhesion agents, or from plastic items often used in human everyday life (packing bags) (Yuan *et al.*, 2022). The physical, chemical, and biological processes will cause these plastics to gradually break into fragments. The two main categories of potential sources of fibrous microplastics are synthetic clothing and industrial products (Yuan *et al.*, 2022). The primary components of synthetic clothing are polyester and nylon fiber, while fibrous microplastics can also be produced by industrial products like plastic films and coil skeletons (Setiadewi *et al.*, 2023). Film microplastics are mostly produced by the fragmentation of plastic packaging bags, whereas pellet microplastics are primarily produced by cosmetics and personal care items including toothpaste, masks, and soaps (Yuan *et al.*, 2022). The majority of the time, the film-like microplastics originate from industrial-grade plastic films like magnetic tapes, X-ray plates, and photographic films, or from packaging products like drinking water bottles, fast food boxes, and preservative films (Zhou *et al.*, 2018). Granular microplastics may have originated from the microspheres found in toothpaste, shower gel, and face wash, among other personal hygiene items (Setiadewi *et al.*, 2023). Furthermore, certain parts and components of specific industries, such as the electronics and automotive manufacturing sectors, may potentially contain granular microplastics. The percentage of fibers and fragments in the influent of four WWTPs in Ningbo City, China, ranged from 76.2% to 84.6% and 9.5% to 12.4% (Jiang *et al.*, 2022). Previous reports had also mentioned the fibers and particles that dominated the wastewater. The handling of textiles and laundry in homes were the primary sources of fiber microplastics in the WWTPs and surroundings. Furthermore, Jiang *et al.*, (2022), mentioned that pellets and films ranged in minor amounts from 0.4% to 4.8% and 1.5% to 8.1%, respectively, in the influent samples in Ningbo City-China. The removal effectiveness of microplastics in the WWTPs may be influenced by the form or shape of microplastics.

2.4 Color of microplastics

The diversity of colors found in microplastics is a reflection of how intricate their sources are. The distribution of various colors varied throughout the treatment units. Setiadewi *et al.*, (2023), stated the majority of the microplastics in the wastewater treatment plant's influent and effluent were clear or white (35%) and black (17–25.4%). Jiang *et al.*, (2022) mentioned that the majority of microplastics in the effluent are black. However, transparent microplastics predominate in the wastewater at various stages of treatment, such as the fine grid effluent in WWTPs (29.0%) (Long *et al.*, 2019; Jiang *et al.*, 2022). The sources of black and transparent microplastics could be plastic bags, cling film, and packaging bags. Microplastics' original brilliant color may become transparent or black as a result of the dye oxidizing, leaching, and aging brought on by weathering and UV radiation in the aquatic environment (Wang *et al.*, 2020). In the influent of four WWTPs analyzed by Jiang *et al.*, (2022) and mentioned that black (i.e., 44.3%, 57.0%, 66.7%, and 68.5% for four WWTPs) was found to be the dominant color followed by red (14.7%, 10.5%, 11.9%, and 3.1%, respectively) and blue (3.7%, 23.0%, 2.4%, 18.5%, respectively in four WWTPs), with minor contributions from the transparent, white, green and other colors. The color of microplastics in wastewater can vary depending on the type and composition of the plastic polymers present. The color of microplastics is an important characteristic that can be used for their identification and characterization in WWTP.

3. Abundance of microplastics in municipal wastewater

Despite an increasing number of papers on the prevalence and success of microplastic removal in WWTPs, the very variable research environments continue to make it challenging to compare various WWTPs (Horton *et al.*, 2017). The variances may result from collection and testing protocols, including sample volume, filtration system mesh size, and analytical methods. For example, the reported abundance of microplastic particles was variable in the influent (12.43 (±2.70) items/L,) as well as effluent (1.23 ± 0.15 items/L) (Bayo, López-Castellanos, and Olmos, 2020). for the removal rate of microplastics, the maximum value was found to be 90.1% a mean value of 87.4% (Bayo, López-Castellanos and Olmos, 2020). The abundance of microplastic particles in the influences of WWTPs varies vary 78.0±2.9, 100.0±3.9, 105.0±5.3 and 65.0±3.1 items/L (Jiang *et al.*, 2022). The source of wastewater includes both domestic and industrial wastewater in some WWTPs. The abundance of microplastic particles in the influents of four WWTPs was significantly varied though they were in the same order of magnitude, which resulted from the difference in population density and industrial activities (Jiang *et al.*, 2022). Variations in recorded concentrations may arise from the use of multiple sampling techniques, including small grab sampling, composite sampling, large grab sampling, etc. in different investigations (Ben-David *et al.*, 2021). Another factor to consider is sample volume; smaller grab samples typically measure higher concentrations than larger samples (Watkins, Sullivan, and

Walter, 2021). Furthermore, the water body sampled, and the filtration mesh size can both have an impact on the concentration that is recorded (Fred-Ahmadu, Benson, and Ayejuyo, 2021). Geographical location can also influence differences in microplastic abundance because various areas may have varying contamination levels and sources (Ivar do Sul, 2021). These differences draw attention to the difficulties in drawing direct comparisons between researchers and stress the necessity of standardized techniques to make inter-study comparisons easier.

3.1 Sources of microplastics with factors affecting

Significant seasonal variations in microplastic levels within wastewater have been shown in numerous studies. The main causes of these variations are changes in the population and the impact of external influences. Seasonal population shifts in coastal areas have been linked to higher microplastic levels in the summer and fall (Cengiz *et al.*, 2021; Akdemir and Gedik, 2023). These shifts are driven by tourism, agriculture, and leisure activities. According to research demonstrating increased microplastic abundance during tourist seasons, tourism operations such as transportation and catering are suspected sources of microplastics (Zhang *et al.*, 2021). For example, increased tourism and leisure activities during these seasons can lead to increased generation and release of microplastics from a variety of sources, such as beachgoers, boats, fishing gear, etc. Furthermore, increased microplastic concentrations in effluent waters during the summer can lead to increased exposure of marine organisms to microplastics. This can have negative impacts on marine life, such as reduced growth, impaired reproduction, and increased mortality. The fluctuations in seasonal population significantly affect WWTPs as they may need to operate at full capacity during summer months, potentially affecting the microplastic load retention efficiency of WWTPs (Akarsu *et al.*, 2020). Furthermore, research by Jiang *et al.*, (2022) suggests that microplastic abundance in WWTP effluent waters is higher in the summer compared to the winter. This difference is partly attributed to the influence of precipitation, with microplastics entering WWTPs varying with the amount of rainfall. During peak tourist seasons, WWTPs may be overloaded, which can lead to decreased removal of microplastics and other pollutants. Some studies propose that precipitation dilutes microplastic levels in discharge waters during rainy periods (Liu *et al.*, 2019). However, others found higher microplastic concentrations during heavy rainfall, possibly due to terrestrial runoff contributing to microplastic mobility (Uogint˙ e et al., 2022). Precipitation can wash atmospheric microplastics into wastewater, and it may enhance microplastic transfer from terrestrial to marine environments (Fok and Cheung, 2015; Kang *et al.*, 2015). Hence, heavy rainfall can wash microplastics and other pollutants from land surfaces into WWTPs, which can also lead to increased microplastic concentrations in effluent waters. Seasonal fluctuations are also evident in the number of microplastics in effluent waters; winter samples show the highest mean MP abundance (Browne *et al.*, 2011; Akdemir and Gedik, 2023). Microplastic concentrations are higher during this season due to increased washing machine usage and increased terrestrial runoff from rainfall (Browne et al., 2011). Washing machines are a major source of synthetic fiber microplastics, while terrestrial runoff is a major source of tire wear particles. Other riverine and marine ecosystems close to urban centers have shown similar patterns of higher microplastic concentrations during wet seasons (Fok and Cheung, 2015; Kang *et al.*, 2018). During wet seasons, microplastics are more likely to be transported from terrestrial to aquatic ecosystems, where they can persist for decades or centuries. Microplastics that are released into aquatic ecosystems during the wet season can be transported to sensitive areas, such as coral reefs and sea grass beds. These ecosystems are particularly vulnerable to the harmful effects of microplastics.

3.2 Fate of microplastics in WWTPs

The microplastics' surface had several imperfections in addition to a rough, broken texture. The contaminants on microplastics may have accumulated from wastewater, suggesting that microplastics may release some pollutants into the environment during treatment at WWTPs. According to certain research, the abrasive action performed during wastewater treatment may have contributed to the rough surface and cracked texture of microplastics. This action may have also altered the microplastics' chemical and physical characteristics (Li *et al.*, 2019). According to Ziajahromi *et al.*, 2017 the majority of microplastics in WWTP influent are transformed into sewage sludge, which then serves as a microplastic reservoir. The variation in microplastic particle abundance in the sludge of different WWTPs was also driven by variations in sludge retention times, which affected the settling efficiency of the sludge. The fact that a significant number of microplastic particles are trapped in sludge suggests that WWTPs are crucial in keeping microplastics out of the environment. Moreover, microplastics can be kept out of the environment by properly disposing of extra sludge. Nonetheless, it is impossible to overlook the release of microplastics into the environment through WWTP effluent (Jiang *et al.*, 2022). The discharge of microplastics into local water receivers through wastewater poses a possible danger to water ecosystems due to their daily emission of microplastic particles. Microplastics are a unique microbial habitat that might selectively enhance antibiotic-resistant genes, raising the hazards to water ecosystems. On the one hand, microplastics have eco-toxicological impacts on aquatic life (Schmidt *et al.*, 2020). The number of microplastics released into effluent can be significantly reduced with the right equipment for the wastewater treatment process. There would be a greater discharge of microplastics from some basic wastewater treatment facilities such as rural residential wastewater treatment if there was no tertiary treatment. Therefore, a significant contribution to the decrease in microplastic emissions is the deeper treatment of household wastewater using the right procedure and equipment (Jiang *et al.*, 2022). Microplastics may have an impact on wastewater's biological treatment. Microplastics might be involved in the movement of media that supports the growth of attached microbes (Bui *et al.*, 2020). According to (Li *et al.*, 2015) biphenyl in activated sludge, leaching from polyvinyl chloride microplastics releases toxicity to limit the activities of heterotrophic and nitrifying bacteria. Furthermore, microplastics in the sludge would negatively impact sludge disposal processes such as anaerobic digestion (Jiang *et al.*, 2022). More hazardous pollutants, such as heavy metals, infections, and persistent organic pollutants, which can be discharged into the environment through a variety of environmental consequences, may be present on the surface of dyed microplastics (Wang *et al.*, 2018). Due to their visual resemblance to the prey, dyed microplastics would be readily consumed by aquatic organisms once they entered an aquatic environment (Jiang *et al.*, 2022).

4. Microplastic removal efficiency of WWTPs

There is a wide range of advanced treatment strategies, even though the nature of primary and secondary treatment is generally constant among studies. The various technologies used in each WWTP have the potential to improve wastewater's ability to remove microplastics efficiently (Table 2). Without making any additional adjustments to the technologies themselves, the comparison performance of each technology is solely dependent on how well microplastics are removed from wastewater. As per the findings of (Hidayaturrahman and Lee, 2019) ozone technology offers a noteworthy degree of microplastic elimination in contrast to filtration methods like membrane disc-filter and quicksand filtration. Different advanced treatment methods can further reduce microplastics before discharge, according to studies comparing microplastics in tertiary vs. secondary effluent (Michielssen *et al.*, 2016; Talvitie, Mikola, Koistinen, *et al.*, 2017; Ziajahromi *et al.*, 2017). In general, it has been reported that membrane bioreactors and sophisticated filtration technologies are efficient ways to lower microplastics in final effluent (Talvitie, Mikola, Koistinen, *et al.*, 2017; Lares *et al.*, 2018).

4.1 Factors affecting microplastics removal efficiency

The removal of microplastics during wastewater treatment is greatly impacted by their density. Low-density microplastics tend to float and can be removed by surface skimming during primary treatment, whereas high-density microplastics settle easily during primary sedimentation (Alavian Petroody, Hashemi, and van Gestel, 2020). PE polymers flow with the treatment processes because their densities are comparable to those of wastewater. PE polymers can be eliminated by flotation and gravity settling, but neither method is an effective means of removing these microplastics in the first place (Bilgin, Yurtsever, and Karadagli, 2020). The effectiveness of conventional WWTPs in eliminating microplastics varies. During the secondary treatment phase, there is a considerable removal of some types, such as polyester, polypropylene, and polyvinyl chloride (Bilgin, Yurtsever, and Karadagli, 2020). Due to their increased densities, certain polymer types, such as pest fibers, exhibit high removal effectiveness and are hence appropriate for flotation (Blair, Waldron, and Gauchotte-Lindsay, 2019; Bilgin, Yurtsever and Karadagli, 2020; Jiang *et al.*, 2020). Technological advancements and innovations are essential for improving microplastic removal rates in WWTPs. For example, researchers are developing new types of membranes that can filter out microplastics of all sizes and densities (Padervand *et al.*, 2020a). Additionally, new adsorbent materials are being developed that can attract and trap microplastics from wastewater. These new technologies have the potential to significantly improve the effectiveness of WWTPs in removing microplastics from wastewater and protecting the environment.

4.2 Innovations in microplastics removal technologies

Innovations in MP removal technologies have been explored in several studies. One approach is the use of membrane technologies, such as microfiltration, ultrafiltration, nanofiltration, reverse osmosis, and membrane bioreactors, which have shown promise in removing microplastics from water and wastewater (Vinay *et al.*, 2023). Another innovative method involves the use of superhydrophobic surfaces, such as a superhydrophobic stainless steel mesh, which can effectively remove microplastics due to their wetting properties (Acarer, 2023). Catalytic degradation and recycling methods have also been investigated, including photocatalysis, advanced oxidation processes, and biotechnology, which can transform microplastics and plastic wastes into environmentally friendly products (Rius-Ayra *et al.*, 2022). Additionally, the agglomeration-fixation of microplastics using organosilanes has shown potential, although the presence of biofilm coverage on microplastics can affect the removal efficiency (Chen *et al.*, 2022). Furthermore, electrocoagulation is an effective method for removing microplastics from wastewater. Shen *et al.*, (2021) found that the removal rate of microplastics by using electrocoagulation is above 80%, and the removal efficiency of fiber microplastics by electrocoagulation is better than that of granular microplastics. Shen *et al.*, (2021) provide feasible operation parameters of electrocoagulation technology in wastewater treatment and evaluate the application prospect of this method in the three-stage treatment system of sewage treatment plants. Overall, these studies highlight the need for further research and development of innovative technologies to effectively remove microplastics from the environment.

Table 1: Microplastic types, sizes, shapes, and colors with microplastic removal efficiencies in different stages of a WWTP (Polyethylene terephthalate (PET), Polypropylene (PP), Polyethylene (PE), Polyvinyl chloride (PVC), High-density polyethylene (HDPE), Polyurethane (PU), Polystyrene (PS), Chlorosulfonated polyethylene (CSM), Ethylene vinyl acetate (EVA), Polyvinyl alcohol (PVAL), Acrylonitrile butadiene styrene (ABS), Polylactide (PLA), Polyacrylonitrile (PAN), Polycarbonate (PC), Polytetrafluoroethylene (PFTE), Polyolefin elastomer (PO), Polystyrene (PS), Polyurethane (PUR) and Nylon 66 (PA66)

Location	WW Type	MP types & Abundance	MP size & Abundance	Shape & Abundance	MP Color & Abundance	MP Removal Efficiency %				References
						Primary	Secondary	Tertiary	Overall	
Turkey	Municipal	PET > PP > PE> polyamide > polystyrene > PVC	102.6 - 4887.5 µm	fiber, film, fragment	-	87.5	-	-	92.1	(Akdemir and Gedik, 2023)
China	Municipal Stormwater	PET,>PP> PE> PE-PP	20–100, 100–200, 200–300,	line/fiber, film/sheet, pellet,	white, black, blue, green	-	92.7 ±6.0	98.1 ±2.0	-	(Zhang *et al.*, 2022)

			300–500, 500–1000, 1000–5000 µm	foam, fragment	, yellow, red, transparent					
Ningbo City, China WWTP A	Domestic	Synthetic cellulose, PET, PE, HDPE, PU, PP, PS, CSM	0.5 – 2 mm >1.1 –1.5 mm > 0.8-1.5 mm	fiber, fragment film, foam pellet	Black, red, blue, transparent, white, green and other	the best removal rate for the fragment (100%) and films (100%)			92.3	(Jiang *et al.*, 2022)
Ningbo City, China WWTP B	Domestic	-	-		black, red, blue	highest removal efficiency for foams (96.7%) - -			95.7	(Jiang *et al.*, 2022)
Ningbo City, China WWTP C	Domestic	-	0.5–2 mm, 1.1–1.5 mm 0.8–1.5 mm			-	-	-	96.7	(Jiang *et al.*, 2022)
Ningbo City, China WWTP D	Domestic wastewater, industrial wastewater	-	-			the best removal rate for the fibers (95.5%) and pellet (100%) shaped			95.4	(Jiang *et al.*, 2022)
Thailand	Municipal	PET, PP, EDPM, Rubber, PS, Acrylic polymer, PU, PA, Alkyd	0.05 –0.5 mm	fragment, fiber, film, bead.	-	25.5% (grit chamber and fine screen)	-	81.91	86.14	(Tadsuwan and Babel, 2022)
Thailand	Municipal				-		-	81.91 with 78.16(UF)	96.97	Tadsuwan & Babel (2022)

						n)				
Oldenburg, Germany	Municipal	PE, PP, PS, PA, SAN, PEST, PVC, PUR, PET, EVA, PVAL (av. 16%), ABS, PLA, paint	50-100 mm (av. 59%), > 250 mm (only 4%)	-	black, blue, red, transparent	-	-	-	97	(Mintenig *et al.*, 2017)
Indonesia, Jakarta	Municipal	-	1001-5000, 501-1000, 301-500, 101-300, 45-100µm	fibers >fragments > films >microbeads > foams	white or transparent >, black > red, blue, green, black, brown, transparent, white, yellow, purple				91.29	(Setiadewi *et al.*, 2023)
Scotland, UK	Municipal	PE, PVC, copolymer, POM, Copolymer films, Protein, Cellulose, PVS s, PP, Lecithin, PP, Cellulose		fragments, films, forms	-	60	68	92	96	(Blair, Waldron, and Gauchotte-Lindsay, 2019)
Daegu, Korea	Municipal	-	-	microbeads, fiber, sheets, fragments	-	62.7	83.1	92.2	99.2	(Hidayaturrahman and Lee, 2019)
Daegu, Korea	Municipal	-	-		-	56.8	75	95.4	99.1	(Hidayaturrahman and Lee, 2019)
Daegu, Korea	Municipal	-	-		-	64.4	91.9	95.7	98.9	(Hidayaturrahman and Lee, 2019)
Detroit, USA	Raw Wastewater		100–1000 µm)	Fragments, fibers filaments, paint chips, micro-beads	-	84.1	93.8	-		(Michielssen *et al.*, 2016)
Northfield, USA	Raw Wastewater				-	88.4	89.8	97.2	97.20	(Michielssen *et al.*, 2016)

Guilin City, China	Raw Wastewater	PP, PE, PET, PAN	500-5 mm	fiber, fragment, film	-	41.20-47.10	-	-	89.20-93.60	(Zhang *et al.*, 2021)
Northern Israel		PE>PVC >PP, PC >PFTE, >PO, PS, PUR, PA66	fiber, 1687–1879 µm (length, 16–19 µm width)	fibers, fragments, films, pellets, beads, foams	Brown>white >black >transparent >fibers - black >blue	-	-	-	97%,	(Ben-David *et al.*, 2021)
China	Municipal and Industrial	PET>PS>PP >PE	63-125 µm 43-63 µm	Fibers pellets fragments granules	black, yellow, red, blue, green, white and clear	-	-	-	90.52	(Long *et al.*, 2019)

Table 2: Microplastic abundance and Removal efficiencies of municipal WWTPs from different locations

Year	Location	Population	Influent (MP/L)	Effluent (MP/L)	Removal efficiency %	References
2023	Turkey	4.89×10^6	76.25±49.2	20.57 ± 21.56	-	(Akdemir and Gedik, 2023)
	Turkey	3.25×10^6	-	-	-	(Akdemir and Gedik, 2023)
	Jakarta, Indonesia	1.25×10^6	17.1±5.65	1.41±0.01	91.29	(Setiadewi *et al.*, 2023)
2022	Turkey	6.5×10^5	-	135.3±28.0	93.7	(Üstün, Bozdaş and Can, 2022)
	Ningbo City, China	-	78.0±2.9	6.0±2.8	92.3	(Jiang *et al.*, 2022)
	Ningbo City, China	-	100.0±3.1	4.3±3.4	95.7	(Jiang *et al.*, 2022)
	Ningbo City, China	-	105.0±5.3	3.5±2.6	96.7	(Jiang *et al.*, 2022)
	Ningbo City, China	-	3 65±4.3	3.0±1.6	95.4	(Jiang *et al.*, 2022)

	Thailand	2.2766×10^5	77±7.21	10.67±3.51	96.97	(Tadsuwan and Babel, 2021)
2021	Turkey	2.0×10^6	72.6	8.2	84.70-93.00	(Vardar *et al.*, 2021)
	Spain	7.041×10^4	3.78±0.48	1.38±0.48	64.26	(Bayo, Olmos and López-Castellanos, 2021)
	Finland	1.6×10^5	61	0.8	99	(Salmi *et al.*, 2021)
	Japan	-	19.16	5.15	95.6	(Nakao *et al.*, 2021)
	England	4.1×10^5	2102.16	129.13	93	(Cunsolo *et al.*, 2021)
	China	-	288.5	22.9	92.1	(Zhang *et al.*, 2021)
2020	Cartagena, Spain	2.1×10^5	12.43±2.70	1.23±0.15	90.10-87.40	(Bayo, López-Castellanos and Olmos, 2020)
	Madrid, Spain	3.0×10^5	171±43	10.7±5.2	93.7	(Edo *et al.*, 2020)
	Karaduvar,Turkey	1.01×10^6	3.1	-	48	(Akarsu *et al.*, 2020)
	Tarsus,Turkey	3.4×10^5	2.6	-	73	(Akarsu *et al.*, 2020)
	Silifke, Turkey	1.2×10^5	1.5	0.9	60	(Akarsu *et al.*, 2020)
	China	1.0×10^5	16	2.9	81.9	Ren et al. (2020)
	China	3.1×10^6	126±14	30.6 ±7.8	75.7	(Jiang *et al.*, 2020)
	China	-	23.3±2.0	7.9±1.1	66.1	(Tang, Liu, and Xing, 2020)
	China	-	80.5 ±6.3	30.3±3.0	62.7	(Tang, Liu, and Xing, 2020)
	Korea	-	10-470	0.004-0.51	98.7-99.9	(Park *et al.*, 2020)
	New South Wales, Australia	-	11.8±1.10	2.76±0.11	76.61	(Raju *et al.*, 2020)
2019	Scotland, UK	1.8×10^5	10-Mar	-	96	(Blair, Waldron, and Gauchotte-Lindsay, 2019)
	Daegu, Korea	-	4200	33	99.2	(Hidayaturrahman and Lee, 2019)
	Daegu, Korea	-	31400	297	99.1	(Hidayaturrahman and Lee, 2019)
	Daegu, Korea	-	5840	66	98.9	(Hidayaturrahman and Lee, 2019)

	Wuhan, China	-	-	79.9 ± 9.3 47.4 ± 7.0 34.1 ± 9.4 28.4 ± 7.0	64.40 - 40.10	(Liu *et al.*, 2019)
	Wuxi, China	-	0.28 (±0.02)	0.13±0.01	53.6	(Lv *et al.*, 2019)
	Wuxi, China	-	0.28 (±0.02)	0.05	82.1	(Lv *et al.*, 2019)
	Beijing, China	2.4×10^6	12.03±1.29	0.59±0.22	95.2±1.6	(Yang *et al.*, 2019)
	Xiamen, China	-	196.00±11.89	9.04±1.12	90-97.15	(Xu *et al.*, 2019)
	Xiamen, China	3.5×10^6	6.55	0.59	90.52	(Long *et al.*, 2019)
	Northern, Italy	1.2×10^6	2.5±0.3	0.4±0.1	84	(Magni *et al.*, 2019)
2018	M-City, Korea	6.77×10^4	23.75	0.33	-	(Lee and Kim, 2018)
	Y-City, Korea	2.3571×10^5	13.5	0.09	-	(Lee and Kim, 2018)
	S-City, Korea	2.452×10^5	10.165	0.1	-	(Lee and Kim, 2018)
	Mikkeli, Finland	-		57.6 ± 12.4	98.3	(Lares *et al.*, 2018)
	Turkey	1.5×10^6	26.55	2.6-8.3	73	(Gündo and Çevik, 2018)
	Turkey	-	23.44	4.11	79	(Gündo and Çevik, 2018)
	Vancouver, British Columbia	1.3×10^6	-	31.1 ± 6.7a 2.6 ± 1.4b 0.5 ± 0.2d	98.3	(Gies *et al.*, 2018)
2017	Sydney, Australia	1.2272×10^6	-	1.5	-	(Ziajahromi *et al.*, 2017)
	Sydney, Australia	6.713×10^4	-	0.48	-	(Ziajahromi *et al.*, 2017)
	Sydney, Australia	1.5087×10^5	-	0.28	-	(Ziajahromi *et al.*, 2017)
	Sydney, Australia	1.5078×10^5	-	0.21	-	(Ziajahromi *et al.*, 2017)
	Helsinki, Finland	-	0.5±0.2	0.3±0.1	40	(Talvitie, Mikola, Setälä, *et al.*, 2017)
	Helsinki, Finland	-	2.0±1.3	0.03±0.01	98.5	(Talvitie, Mikola, Setälä, *et al.*, 2017)
	Turku, Finland	-	0.7±0.1	0.02±0.007	97.1	(Talvitie, Mikola, Setälä, *et al.*, 2017)
	Hameenlinna, Finland	-	2.0±0.07	0.1±0.04	95	(Talvitie, Mikola, Setälä, *et al.*, 2017)

	Mikkeli, Finland	-	6.9±1	0.005±0.0004	99.9	(Talvitie, Mikola, Setälä, *et al.*, 2017)
	Helsinki, Finland	8.0×10^5	380 ± 52.2, 686.7±155	-	98	(Talvitie, Mikola, Setälä, *et al.*, 2017)
	Oldenburg, Germany	2.1×10^5	-	-	-	(Mintenig *et al.*, 2017)
	Netherlands	-	68	51	25	(Leslie *et al.*, 2017)
2016	Scotland, UK	6.5×10^5	-	15.70±5.23	98.4 - 92.6	(Murphy *et al.*, 2016)
	Detroit, USA	-	-	5.9	95.6	(Michielssen *et al.*, 2016)
	Northfield, USA	-	-	2.6	97.2	(Michielssen *et al.*, 2016)
	Los Angeles, USA	-	0.08	0.00088	99	(Carr, Liu, and Tesoro, 2016)
	USA	6.136×10^7	-	5.0×10^4	-	(Mason *et al.*, 2016)
2015	Helsinki, Finland	8.0×10^5	610	8.6±2.5	-	(Talvitie *et al.*, 2015)
	Paris, France	-	260–320	14–50	-	(Dris *et al.*, 2015)

2. Conclusions

The thorough analysis emphasizes that secondary and tertiary WWTPs contribute significantly to microplastic contamination since they regularly release substantial amounts of wastewater into the environment. A comprehensive overview of the microplastic types, sizes, forms, and colors present in wastewater, as well as their origins, removal efficiency, consequences for wastewater treatment, and fate, is given in table 01. The most abundant microplastic types are PE, PP, and PET. Fiber, film, and fragment shapes were identified as the most abundant microplastic shapes and when considering the color, black is the most abundant color followed by red, blue, transparent, white, green, and other colors. Understanding the variety of microplastics and how well they can be removed is essential to tackling the growing environmental problem. In this study, it was concluded that the removal efficiency of microplastics in a municipal WWTP varies between 86.14 – 99.1%. It was concluded that future studies ought to explore the intricacy of these relationships to expand on current understanding and develop sustainable wastewater treatment strategies.

Recommendations

Future research should focus on studying different types of polymers, not just the commonly studied ones. Additionally, it should consider variations in microplastic concentrations over time and explore how changes in tourism, agriculture, and demographics affect wastewater treatment. More research is necessary to understand how precipitation affects microplastic dynamics in WWTPs. Approaching the problem of persistent microplastic pollution in aquatic ecosystems requires a sophisticated understanding of the interactions between human activity and environmental conditions. Furthermore, it's also important to evaluate new treatment methods such as electrocoagulation for their effectiveness in removing microplastics.

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CASE STUDIES OVER THE FAILURE OF ONSITE SEWERAGE TREATMENT SYSTEMS IN SRI LANKA

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Abstract: On-site sewerage treatment systems are the widely used system in the Sri Lankan context to treat sewage, the process of treating sewage is expected to ensure human health and safety. However, urbanization, converting natural environments to built environments, and changes in hydrological and meteorological conditions have been affecting failing sewerage treatment systems while creating health hazards and safety issues. Sewage is a hazardous waste containing pathogens that can pose significant threats to warm-body species like humans, and it creates diseases and impacts environmental pollution. Hence, the study entails determining why on-site sewerage treatment systems fail in the application stage within a short period, with the objectives of investigating potential causes for failures and determining whether septic system malfunction occurred as a result of a difference between considered design conditions and actual conditions at the application stage. In finding out the applicable causes, a background analysis has been carried out by referring to literature and case studies for five cases where a recently implemented septic system failed. The provided systems for the considered cases have been checked against actual site conditions at the application stage, and the standards followed for proposing the same system. With the results of the study, it was found that, when providing the On-site sewerage treatment system, the actual site condition available had been neglected carelessly. Available soil characteristics, ground conditions, actual percolation rates, seepage paths, environmental factors, and physical factors affecting sewerage treatment should be taken into consideration and addressed before proposing an On-site treatment system. On-site sewerage treatment systems are one of the key components in any building. Its performance will enhance the quality of human life in the long run, but it is identified that the value given for implementing a practical and applicable system is not at an acceptable level.

Key Words: Septic System; Soakage pit; Effluent; Percolation

1. Introduction

From ancient times to date some, of the practices related to human health and hygiene have not changed in Sri Lanka. One such practice is applying an onsite disposal system for sewage waste and effluent disposal to the ground. The conventional type of installation of the septic tank and soakagepits onsite is typical to all urban, suburban, and rural areas except for the Colombo city limit.

In the modern world health and hygiene are considered as one of the factors to determine the development of a country and in those criteria, sewage disposal, treatment, wastewater disposal, and treatment play a major role. Therefore, ensuring the quality of treatment is a key factor to be considered when designing, executing, and maintaining the septic tank with soakage pit wherever to be implemented. The case is that, currently septic tank and soak-age systems implemented in medium-scale buildings have been failing. Hence, the study involves identifying the main reasons for these failures.

Well-maintained septic tank systems and soakage pits can be subjected to clogging and then fail upon with accumulation of non-decomposing matterswithin the system or else the system can fail due to a change of theoretical aspects over the design of the septic system as the use of the building, increment of several occupants, land use change of neighboring lands, where these effects on changes on parameters taken at the design stage. However, these can be overcome with simple alternation methods to the system. But ifthe system fails due to changes in soil characteristics, Ground elevations, changes in natural underground seepage paths, and the rising of the ground-water table, then the mitigation method for those can be applicable or sometimes not. Further, it cannot be identified simply without an investigation.

1.1. Background

Sri Lanka, a tropical country with 65,610 sq. km of land and 20 million inhabitants, has experienced significant land use and climate change over time. The current situation in the western province is influenced by changesin land use, land reclamation for infrastructure improvement, increasing de-forestation, decreasing natural waterlogged areas due to urbanization, and expanding flood plains. On the other hand, it is common that Septic tank andsoakage systems have been found to fail in Sri Lanka, despite their design to withstand capacity. Changes in topography, geography, and hydrology may impact the implementation of an onsite treatment system Standards Institute of Sri Lanka published 2004 the Code of Practicefor Construction of Septic Tanks which outlines methods for wastewater disposal and desludging, with flow estimation included but not regulated. However, most designers assume individual tanks and soakage pits will notfail if designed based on the required capacity, despite the need for prior testing.

Understanding the reasons behind failures in the On-site treatment system has become crucial for future projects and justifying new steps in proposingan on-site sewerage treatment system upgrade. Investigating these factors can help overcome past practices and improve the effectiveness of on-site sewerage treatment systems.

2. Objectives and Methodology

This study will involve finding reasons why septic systems fail in the application stage within a short period even though the system is newly constructed, renovated, or improved. In some cases, the system fails in the application stage though the same systems were successfully used in the past and designed for the required capacity.

To achieve the expected aim, objectives have been developed for the study,

1. To Investigate possible causes for failure in septic systems within a shortperiod.
2. To Investigate whether septic system malfunction occurred due to the difference between considered design conditions and Actual conditions at the application stage.

3. To provide recommendations and solutions to overcome the matter.

Considering the foregoing and determining the appropriate causes, a background analysis was performed by referring to a wide variety of literature toestablish the fundamentals of septic systems and the causes of septic system failure. The common relevant causes and special causes of septic system failures are subject to be determined. It was found there could be common causes and site-specific causes. Depending upon the findings, the study looked at five genuine examples where they failed in a short period*and were exposed to a check upon failure to discover the closest reasons.

(* A short period can be simply defined as less than 1 year where a septic system is to be designed and implemented for at least a 1-year)

Accordingly, five cases were examined by identifying their background, design concerns, theoretical features, and site conditions, as well as practical aspects in the application stage.

The selected five cases are,

1. Rehabilitation Hospital, Ward 12 (RRH)-Ragama,
2. Rehabilitation Hospital Main Physiotherapy Unit (RRH)- Ragama,
3. National Institute of Traditional Medicine (NITM)-Navinna,
   Industrial Development Board Regional office (IDB) – Gampaha,
4. National Police Academy (NPA) -Katana.

Figure 1-Locations of Case Studies.

A structured interview was conducted with building residents to collect information as follows using a well-prepared questionnaire to determine the likelycauses of septic system failures.

- History of the premises.
- Current building Use and building use in the past
- Number of occupants current and in the past
- Times of day when the building is utilized by occupants and howmany
- Land uses
- Structure arrangement within the land
- Septic system location, adopted method, and capacity designed for
  The behavior of the system with time and are there any critical incidents engaged with

system failure
- Details of desludging and cleaning events and how often they werecarried out.
- Maintenance systems, adopted to maintain the septic system
- Considering the past 5 years' changes within the drain field orground (Manmade or natural as observed by occupants)
- Details of cleaning agents, Quantities, and Frequency of cleaning
- Observed behavior patterns of the septic system before and current

Aside from the aforementioned site inspections, data on general site conditions such as topsoil condition, ground elevations, slopes, accessible soil types in the surrounding area, and water sources within the site premises have been inspected and relevant data have been collected. (Table 1) Collect data on existing or proposed septic systems concerning their design.

The obtained data on the septic system's history was then compared to current usage habits to discover any probable reasons for system failure related to improper septic system utilization. (Table 2)
The collected data is then evaluated to determine any changes in ground conditions due to earth filling, compactions, new surrounding buildings, andother factors that will affect changes within the drain field or ground condition.

The current septic system available at the location (Table 3) is then checked as specified in code of practice SLS 745 -2004 -part 2 to determine whether the correct technique was followed when designing or, if not, to determine the impacting parameters regarding the septic system that is failing about the design provided.

For each location, two percolation experiments were performed to assess thepercolation rate for the systems as regulated by the SLS745. (Eq. 1) To determine the actual water table, measure the surface depth of water in surrounding wells.

$$\text{Percolation rate (mm/h)} = \frac{150\text{ (mm)}}{\text{Time taken to drain outthe water in the pit (h)}} \qquad (1)$$

Concerning available data on the current septic system, Flow estimationhas been computed based on the existing use of the building and the applicability of the offered septic system for the premises, taking into account all external facts and the required septic tank capacity.

Check that the assumptions made by designers during the design stage werecorrect and appropriate to the septic system based on the actual soil conditions discovered. By comparing standards regarding design considerations and proposed or operational septic systems, and then evaluating actual consequences and how they affect wastewater treatment.

Table 1- Details of Site Inspections-General background

No	Name of the project	Users of the Building	Natural features around the location of the septic system					Existing Ground Condition			Details of Water Table		Manmade features around the location of SS		
			Availability of trees			Availability ofgrass cover	Availability of plants and shrubs	Elevational behavior	Condition of surface	Soil behavior to the naked eye	Source	Water table (Depth in m)	No of Perma-nent structure	Use of the building of SS attached to	Times duration where the building is utilizing considering to a day
			Small	Average	Huge										
1	Regional Office for IDB-Gampaha	Office staff	3	1	-	Covers entire area	Covers 3/4area	Almo stflat	Wet	Sandy, Light brown	Well	2.50 -2.80	1.00	The office staff of 30 Members and 5-10 Public	7.30 Am to 5.00 Pm
2	Ward No 12 forRRH-Ragama	Nursing staff and Patients	-	-	-	Covers 3/4 area	Covers 1/2area	Sloped	Dry	Dark Orange plus Yellow hard dense soil	Well	3.00 -3.500	1.00	Nursing staff and disabled patients-75 occupants	The whole daypeaks in the Morning
3	Improve ment to MPT unit for RRH-Ragama	Thera-pists and Patients	-	-	-	Covers 3/4 area	Covers 1/4area	Almo stflat	Dry	Dark Orange + yellow Hard dense soil	Well	3.00 -3.501	3.00	Nursing staff and disabled patients-150 occupants	Whole day working hours
4	Male Hostel block for NPA-Katana	Senior Police Officers	3	2	-	Covers entire area	Covers 3/4 area	Almost flat	Wet	Sandy, Light brown in color	Well	2.50 -2.80	2.00	Senior police officers 130 accommodation capability	peak in the Morning and Evening
5	Improve ment to the kitchen and minor staff block at NITM-Navinna	All staff and NITM minor staff	8	2	-	Covers 1/4 area	Covers 3/4 area	Almost flat	Dry	Black to brown dusty soil on the sur-face	Well	3.00 -3.501	3.00	The office staff of 90 Members and the public	In the morning and for breakfast, Lunch

Table 2-Details of existing septic systems at locations considered

No	Name of the project	The typeof Septic system used	No of Occu-pants	Peak time of washroom utilizing	Buil ding Catego ry	for the past decade/5 years no of times de-sludging car-ried out	Dimensions of Septic tank			Dimension of Soak-age pit		Constructed with
							Length (mm)	Width (mm)	Depth (mm)	Diamete rin (mm)	De pth (m m)	
1	Construction of Regional Office for IDB- Gampaha-Stage 1	N/A	N/A	N/A	Office	N/A	N/A	N/A	N/A	N/A	N/A	N/A
2	Renovation and im-improvement to Ward No12 for RRH-Ragama	Septic Tank and Soakage pit	Max 50	6.30 am - 8.00 am	Hospital	every 6 months	1500	1200	1500	1200	1500	Concrete
3	Renovation and improvement to MPT unit for RRH-Ragama	Septic Tank and Soakage pit	Max 100-125	7.30 am - 5.30 am	Hospital	every 6 months	1200	1000	1200	1200	1200	Masonry walls
4	Construction of male Hostel block for NPA-Katana	N/A	N/A	N/A	Accom modati on	N/A	C	N/A	N/A	N/A	N/A	N/A
5	Renovation and \ improvement to the kitchen and minor staffblock at NITM-Navinna	Septic Tank and Soakage pit	Max 75	7.30am - 9.00am and 11.3am - 1.30pm	Restaurant +resident	every 3 months	1375	1050	1200	1000	1200	Masonry walls

Table 3- Details of the New septic system for the considered locations

No	Name of the project	Type of Septic system Pro-posed/casted	No of Occup ants	Peak timeof wash room utilizing	Building Category	Times that de-sludging carried outafter new construction/ renovation	Dimensions of Septic tank			Dimension of SP		Constru cted with	Year
							Leng th (m)	Width (m)	Depth (m)	Diamet er in (m)	Depth (m)		
1	Construction of Regional office for IDB-Gampaha-Stage 1	Septic Tank and Drainage trench	35-45	7.30am - 9.00am and 3.30pm - 5.00pm	Office	Twice a year Upto Date	2100	1000	1500	1200	2400	Concrete	2022
2	Renovation and improvement to Ward No 12 for RRH-Ragama	Septic Tank and Soakage pit	Max 70	6.30am - 8.00am	Hospital	every 6 months	3300	1150	1500	1800	2400	Concrete	2020
3	Renovation and improvement to MPT unit for RRH-Ragama	Septic Tank and Soakage pit	Max 150-175	7.30am - 5.30pm	Hospital	every 3 months	5250	1250	2400	1200	3000	Masonry	2019
4	Construction of male Hostel block for NPA-Katana	Combined two Septic Tank and Single Soakage pit	Max 300	6.30am - 9.00am and 5.30pm - 6.30pm	Accomm odation	N/A	5250	1250	3000	1200	3000	Concrete	2023
5	Renovation and improvement to the kitchen and minor staff block at NITM-Navinna	Septic Tank and Soakage pit	Max 90-125	7.30am - 9.00am and 11.30am - 1.30pm	Restau-rant + resi-dent	every 3 months	4375	1250	2400	1200	2800	Concrete	2019

3. Data Analysis and Results

Considering to the project is located in the Gampaha district in Gampaha town proximity (Figure 2) and is mostly considered a dry town. However, itis found that in the past three to five years some of the areas of the town have been flooded during monsoon rains and inter-monsoon rains due to not having a proper drainage system for rainwater disposal.

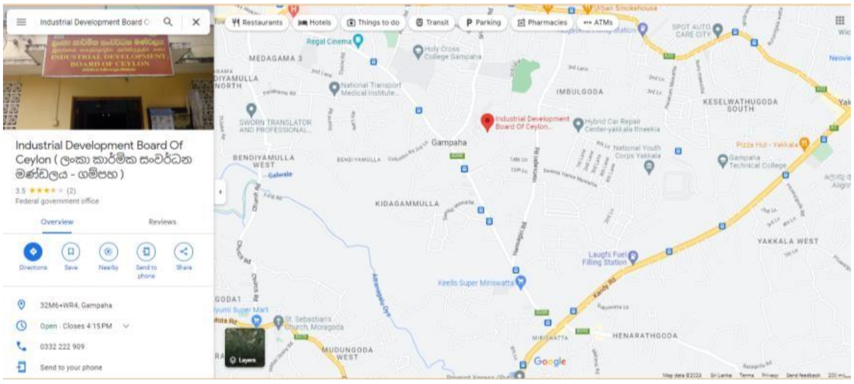


Figure 2-Industrial Development Board-Gampaha.

The regional office for IDB- Gampaha has requested and proposed astory building and only one story completed in 2022. The key facts found by the background details collected from the survey have been tabulated in Table 4-Background Details of IDB-Gampaha. The current condition of the location is as Figure 3. The subjected area gets floodedsometimes due to heavy rain and the ground gets easily saturated withthe heavier rain.

Figure 3- A constructed project with Septic Tank.

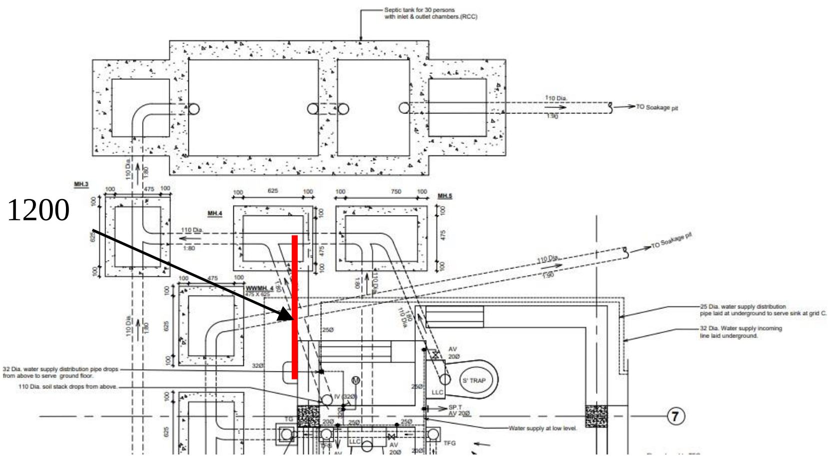
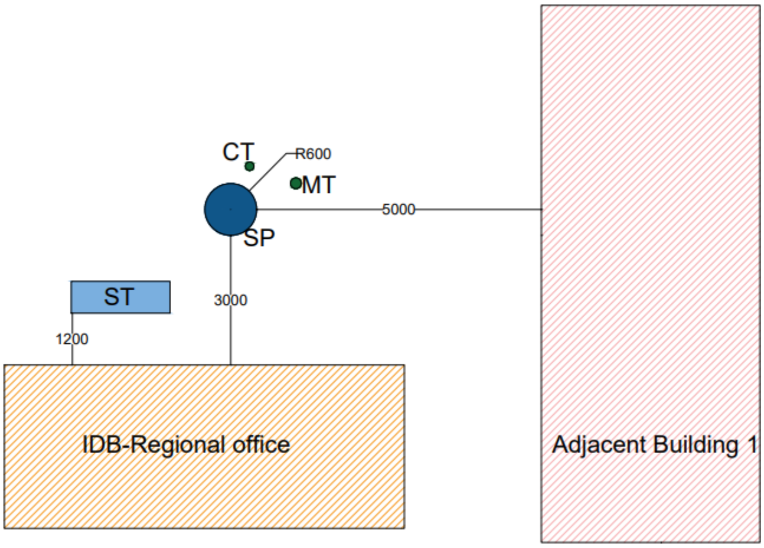


Figure 4-Part plan of the septic Tank.

Table 4-Background Details of IDB-Gampaha

Background of Project	
Brief	A two-story building proposed for the regional office of IDB and only one story constructed
Intend Use of Building	Office
Number and Type of Users	30 – Daytime Employees
	10- Visitors per day
Time of Use	7.30 am to 5.30 pm
Site plan and surrounding	
Natural Drainage and Ground Water Table	Below 2.5 m from EGL
Soil Condition	Filled Material with a combinationof Soil types
	Sandy, light brown to Dark Brown
Percolation Test	Not Done
Elevations	Almost Flat
Existing Soakage Pit	Non
Maintenance Capabilities	Non
Neighboring land use and environment	Government Offices in nearby lands
Proposed / Casted / Renovated / Improved Septic System Details	
Septic System	Septic and Soakage, proposed 30 persons
ST Dimension in mm (L x W x D)	2100 x 1000 x 1500
SP Dimension in mm (Día x D)	1200 x 2400
Year Casted/ Improved	Aug-22
No of Years Designed for	3
Times that desludging carried out afternew SS implementation	2 times as of December 2022
Does this happen due to common reasons	No

According to the site inspection carried out, it was observed that the septic tank and socage pit were constructed on the rear side of the building in an open space, were 1.2m and 3m away from the new building respectively. It was observed that another building was constructed 5m away from the socage pit. A coconut tree and a mango tree were right next to the socage pit. Refer to sketch no 1.



Sketch 1-Plan view sketch of location.

A percolation test for two test pits was carried out where two pits are1.2m away from each other and near the socage pit. When digging pit1 the top layer (up to 300mm) found was a construction waste-filled material and beyond that level light brown sandy soil, another filled material soil mix was found.

Figure 5- Percolation Test Pit 1 and Pit 2.

Both pits were tested for percolation rate and average percolation forthe area was calculated. The collected data and on-site test results were then used to check against the standard given in SLS-745 for a septic tank and socage pit by calculating the Average daily flow, working capacity applicable, and Minimum Surface area required forseptic tank and socage pit. all the parameters are analyzed by comparing them to the standards to be followed as guided by SLS -745. The analyzed facts for the septic tank and socage pit for the project are as in Tables5 and 6 respectively.

Table 5 - Analysis of the proposed Septic Tank (ST) and Constructed ST at the site for Project 1

Standard Requirement for ST by SLS 745	**ST Designed for**	**ST Constructed with**
Should be watertight	Satisfied	Satisfied
locate in an Open area	Satisfied	Satisfied
Sufficient access to be provided for de-sludging activities	Satisfied	Satisfied

Tank length should be 2 to 4 times of width		Satisfied	Satisfied
1m3 < Working Capacity (m^3) < 12m^3		Satisfied	Satisfied
Required Min^m Surface Area (m^2)	All Waste =1.34	Satisfied =2.10	Satisfied =2.10
	Blackwater =1.22	Satisfied =2.10	Satisfied =2.10
Septic Tank designed for		Blackwater	Blackwater
Width = or > Min^m Width of 750mm		Satisfied	Satisfied
Min^m Depth = or > 1m below liquidlevel		Satisfied	Satisfied
Inlet -Tee fitting, extended to 20% be-yond liquid level		Satisfied	Satisfied
Outlet -Tee fitting, extended to 300mm beyond liquid level		Satisfied	Satisfied
Maintain a 50mm difference between in-let invert level and outlet invert level		Satisfied	Satisfied
Should be 200mm freeboard		Satisfied	Satisfied
Should keep 100mm min^m height opening within the chamber partition		Satisfied	Satisfied
Each chamber shall provide with 25mm dia Vent pipe up to a height where sufficient to avoid odor nuisance		Satisfied	Satisfied

Table 6 - Analysis of the proposed Soakage pit (SP) and Constructed SP at the site for Project 1

Standard Requirement for SP bySLS 745	**SP Designed for**	**SP Construed with**
Water Table > 2.5m EGL	Assumed >2.5m	Seasonal GWT reaches2m from EGL
125mm/hr. =/>Percolation Rate>25mm/hr.	Assumed as 125mm/hr.	Actual PR = 274 mm/hr.
Keep 18m away from the nearestWell	Satisfied	Satisfied
Keep 5m away from the nearestBuilding	Satisfied	Not Satisfied
Keep 10m away from the nearestSoakage Pit (ADF =1.6m^3/d)	Satisfied	Satisfied
Specific Effective Area requirement= 6.6 m^2	Satisfied	Satisfied
3000mm > Min^m Dia / Width >900mm	Satisfied	Satisfied
Depth to GWT from the bottom ofSP =3m	Satisfied	Satisfied

According to the comparison between the proposed system vs constructed system, it is indicated that due to not considering site-specific data such as actual ground conditions which affect the percolation rate of the socage pit, the actual depth to be kept from GWT tothe bottom of SP may affect the failure of the system. In SLS 745it mentioned that no socage pit, seepage bed, or trench should be used where the percolation of the ground is more than 250 mm/hr which was violated by the implemented system.

The percolation rate calculation under saturate conditions for the project is as in Table 7 and the average percolation rate -APR for pit 1 is 390.22 mm/hr where the soil is not suitable for treating the effluent discharged from SP, but then again for the pit 2 APR is equal to 157.79mm/hr where a decision over suggesting seepage bed can be applicable. However, since the septic system has already failed two times for the considered year though the building is not functioning atits full capacity, we can conclude that the proposed system is not suitable for the project due to the poor soil condition available at the site.

Furthermore, for pit 2, and observed that water accumulation in the pit on rainy days due to direct mango tree roots creates a pores path to the pit. We can assume that on continuous rainy days where ground saturation is obvious these root paths will lead water to the socage pit and rainwater accumulation within the pit. This also affects septic system backflow and fails the whole system by overflowing with contaminated water.

Table 7-Percolation Test for IDB-Gampaha

Location	IDB	
	Pit 01	Pit 02
Invert level of SP from EGL	350	350
Set 01		
Start Time	8.30 am	8.30 am
Time taken to drain out 150mm height (minutes)	17	53
Percolation Rate (mm/hr)	529.41	169.81
Set 02		
Start Time	12.45 pm	12.45 pm
Time taken to drain out 150mm height (minutes)	25	63
Percolation Rate (mm/hr)	360.00	142.86
Set 03		
Start Time	4.00 pm	4.00 pm
Time taken to drain out 150mm height	32	56
Percolation Rate (mm/hr)	281.25	160.71
Average Percolation Rate Per Pit	390.22	157.79
Average Percolation Rate	**274.01**	

For project 1 the proposed system according to the guideline drawing basedon the number of occupants under the assumption that the working capacityis less than $12m^3$ has been perfectly aligned with the actual condition construction for the septic tank but neglects the actual soil condition which directly effects on treating the effluent within the socage pit make the whole system fail and create hygienic issues.

The actual land formation in this area has been adjusted by humans by fillingup the ground to create more flat surfaces to construct the building,but when proposing a shallow-depth septic system, the same fact has been neglected. Also, as a solution to this project, a horizontal flow-secondarywetland can be proposed or a seepage bed combined with a percolation bedcan be provided.

Likewise, all cases have been analyzed for result generation and to determine the potential causes for on-site treatment systems to fail.

4. Discussion

Septic systems are key components in any building and are concerned with their durability. Its performance will enhance the quality of human life. However, in some cases, it creates the most unbearable experience in humanlife.

When considering the literature most of the papers conducted concerning the field of the study recommend considering actual site conditions when proposing a septic system. Some literature emphasizes that theavailable soil and ground condition will directly affect the functionality of the proposed system and it should be considered when proposing a suitablesystem.

However, the result of the study, shows that in the proposing stage for all five cases, no such consideration has been given to identifying the effect ofground behavior and soil type over the proposed septic system. For some projects, it was found complete soil investigation had been carried out but in consideration of proposing the septic system, it's been neglected. Furthermore, hence in the application stage ground condition neglection has affected the functionality. It is identified though, in SLS 745, the guideline provides by indicating the minimum distances such as,

Keep 5m away from the nearest Building

Keep an applicable minimum distance away from the nearest SoakagePit, also not been considered in the application stage. Since a governing ruleimposed by urban, municipal councils to keep 50ft away from the nearest well has been considered and applied but not the 60ft guided by the standardapplicable for Sri Lanka. This is also a contributing factor to failing the septic system in the application stage since keeping build-up spaces, and well-compacted earth beneath it will reduce the natural percolation which affects on reduction of percolation by the effective area of the Soakage pit. However, by analyzing the data for the above-considered five cases it is identified that any build-up permeant structure may affect reducing percolation. Specifically retaining walls, Deep foundations, Boundary wall foundations, etc. Therefore, when proposing a location for a septic system these factors need to be considered to ensure the functionality of the system.

Considering all five projects and in general in Sri Lanka, common practice is to adopt a Septic Tank plus Soakage pit as the septic system, this decision mostly depends upon the assumption that the working capacity of the septic tank is less than $12m^3$ and on the number of occupants but in special cases, as found in Rehabilitation Hospital and Katana Hostel project it can exceed though the number of occupants is in the same range. Hence, conducting separate complete calculations in deciding effective areas when suggesting a septic tank and soakage pit will ensure the applicability of the system and if not propose an applicable system. This will minimize the failure of anunsuitable system.

It is found most of the considered projects haven't followed the exact guidelines in proposing the septic system and in many Sri Lanka projects exact guidelines won't be used in proposing a suitable septic system. With urbanization and changes in hydrological and metrological patterns, the environment around us has changed. Hence, following the guideline in proposing, designing a Septic system is essential and will minimize the risk of failure of the system. As humans in the modern world, a septic system is a basic requirement in today's lifestyle but the consideration given is less when concerned with the functionality of the system. Throughout the study, it is identified that the general guidelines were carelessly neglected in both the designing and application stages. The no of occupants and peak hours may beconsidered in calculating, designing, or proposing a system, but the effect of other parameters in the application stage has not been considered, or analyzed concerning the functionality of the system. Hence, it is obvious that the proposed system won't be able to fulfill the requirement required for functioning the septic system which eventually leads the system to fail.

5. Conclusion and Recommendation

This study concludes when designing, proposing, and implementing a septic system even with a Repair, Rectification, or Renovation that available soil types around the proximity of the proposed septic system location, Ground Conditions, Buildings, and any parament structures within the 5m proximity and their foundation, Slopes and elevational differences within the area been neglected and respective actual calculations, guidelines not been followed hence, the accumulated contribution ultimately effect on un-predicted system failures in a short period.

Affecting risk factors and environmental variables will differ from locationto location as same as shown by this study. The considered five location reasons causing system failures are different and the rates of their influencesare different. Identifying these factors in the designing stage will help the designer to provide the best option for the building. Further, depending uponthe facts identified by the study to achieve a better-performing septic system,an actual site inspection should be carried out rather than proposing a systembased on the occupants, following a typical guideline prepared years ago fora building. It is recommended, when designing, proposing, and implementing a septic system even with a Repair, Rectification or Renovation must bethoroughly checked against the,

1. Available soil types around the proximity of the proposed septic system location at least for a 5m dia buffer area.
2. Site condition and Ground Condition within the proposed area.
3. Actual Percolation Rate.
4. Buildings and any parament structures or any other physical structures within the 5m proximity and their foundation depth are likelyto be.
5. Slopes and elevational differences within the area.
6. Factors affecting decreasing the productivity of the effective area.
7. Environmental factors such as trees available, Vehicle movement, etc.

It will not only ensure the identification of factors that affect effluent treatment with consideration of the above-mentioned facts but also by predictingthe future changes within the ground concerning the building purpose and functionality or by considering the changes in neighboring land foundations. In addition to the above, with the study, it is identified that storm-water percolation and infiltration behaviors within the area with the effect of root intervention by larger trees may affect the septic system. Since soakage pits are semi-pervious tanks, nearby roots help easy percolation of stormwater towards the soakage pit and accumulation of storm water insidethe pit. Hence, as a further investigation to the study, studying the effect of the root distribution patterns within the area, stormwater flowing patterners identification through the soil profile can be carried out.

Analyzing the risk factor and how it changes with permeability, percolation,and infiltration in the area will ensure the planned septic system's quality. Septic systems can be constructed to treat all wastewater, grey water, or black water, and whoever implements the system should consider the design criteria of the system to connect the pipelines to the system suitably duringthe application stage. In the Sri Lankan context, this information is not wellcoordinated from the design stage to the implementation stage, resulting in system failure. As a result, people must be educated on the distinctions and behavior of all waste, grey water, and black water when they are forwarded to a septic system.

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A REVIEW OF IMPACTS OF OCEAN ACIDIFICATION ON CORAL REEFS

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Abstract: Coral reefs are rich in marine biodiversity and essential for maintaining the ecosystem as they provide extensive ecosystem services such as creating breathing environments for marine lives and providing storm protection with regulating erosions. Human activities, both direct and indirect, are causing coral reefs to become endangered. Due to climate change, reef diversity and coral growth are depleted, and this will create adverse effects on the existence of all living beings. This review paper examines the impact of ocean acidification on coral reefs through the process of coral calcification. The main cause of ocean acidification is identified as the high uptake of carbon dioxide from the atmosphere by the ocean, which is primarily caused by the burning of fossil fuels. The paper compares various solutions for addressing ocean acidification and finds that mitigation strategies have high feasibility and potential. It is identified that there is currently a dearth of information regarding the combined effects of ocean warming and acidification on coral reefs, which is the actual situation.

Keywords: Ocean acidification; Coral calcification; Climate change; Solutions; Anthropogenic carbon dioxide emission

1. Introduction

Coral reefs are one of the most valuable eco-ecosystems for biodiversity. Even though much less than 1% below the sea surface is included with corals, they assist about one zone of marine residing sources (Albright & Cooley, 2019). Like serving as a hot spot for biodiversity, coral reefs offer financial and social services that are critical to human lifestyles. Coastal safety, food production, and enhancing the tourism industry are some of them (Allemand & Osborn, 2019).

Unfortunately, coral reefs have become one of most of the world's most endangered environmental systems. There are several threats such as overfishing, unsustainable tourism, coastal pollution, global warming, and the acidification of the oceans. (Allemand & Osborn, 2019). This study discusses the link between ocean acidification and coral degradation.

Because of the atmospheric depletion of carbon dioxide in seawater, oceanic acidification occurs. As the acid stage rises, more H + ions react with carbonate ions in seawater and produce bicarbonate ions. This could reduce oceanic carbonate concentration (Harvell et al., 2007). Therefore, oceanic acidification will sluggish down the calcification procedure of reef-constructing structures manufactured from calcium carbonate (Anthony et al., 2008).

In this paper, the first section discusses the importance of coral reefs through biological, ecological social, and economic aspects. The second section explains how ocean acidification affects the calcification process of corals, with the help of oceanic carbonate chemistry. In the last section, currently proposed solutions to mitigate ocean acidification impacts are compared by taking into consideration their feasibility and potential.

The review included studies published between 1976 and 2021 that examined the impact of ocean acidification on coral calcification. The literature search was conducted using databases such as Google Scholar, Scopus, and ScienceDirect, and the search strategy involved targeted keywords, including ocean acidification and coral calcification.

2. Importance of Coral Reefs: Biological, Ecological, Social, Economical

2.1 Biological and Ecological Importance

Coral reefs provide many significant biological and ecological services which make them essential for the existence of life. Even though coral reefs cover a small area of the ocean, Allemand & Osborn (2019) have stated that species diversity is 400 times higher than in other areas in the ocean, which is approximately equal to the species diversity in a square kilometer in a large rainforest. Furthermore, coral reefs provide ecological services and goods for example renewable resources, coral mining, physical structure services, biotic services, biogeochemical services, and information services (Moberg and Folke, 1999).

2.2 Social and Economic Importance

While acting as an “ecosystem engineer” (Allemand & Osborn, 2019), coral reefs play a major role in a country’s economy as well as society. As reef systems are rich in marine diversity especially fisheries, corals act as a source of food. The general types of seafood products provided by coral reefs are fish, mussels, crustaceans, sea cucumbers, and seaweeds (Moberg & Folke, 1999). Corals contribute to the country’s economy mainly through tourism. For instance, annually two million tourists come to Australia only to visit the Great Barrier Reef (Allemand & Osborn, 2019). Also, it is identified that 15% of the gross domestic product (GDP) of most of the small developing islands like the Caribbean, Hawaii, Philippines, and Indonesia comes from reef-related tourism (Burke et al., 2011). Coral reefs also create job opportunities for local communities such as the fishery industry, lime production, cement manufacturing, jewelry, and souvenir industries. Lebrec et al (2019) have mentioned tourism contributes to 40% of the country's employment in Palau where 86% of total tourists visit there only to dive and snorkel on coral reefs. Also, it has been identified that restoring and management of coral reefs are cost-effective compared to implementing tropical breakwaters (Ferrario et al., 2014).

3. Ocean Acidification and Coral Degradation

3.1 Ocean Acidification

There are three drivers of ocean acidification have been discussed in (Billé *et al.*, 2013). They are the uptake of atmospheric CO_2 by the ocean, eutrophication, and ocean warming. eutrophication is an excessive production of algae in coastal waters due to coastal pollutants. This causes ocean acidification as algae produce CO_2 through its microbial respiration process (Cai *et al.*, 2011). Ocean warming indirectly affects ocean acidification by dissolving Methane Hydrates which currently exist in a solid state in the deep ocean. Therefore, this is identified as a future driver for ocean acidification under increasing global warming (Billé *et al.*, 2013). Yet the main reason for ocean acidification is identified as up taking of atmospheric CO_2 (Billé *et al.*, 2013). Because, dissolving atmospheric CO_2 in the atmosphere will reduce the pH in the seawater which makes seawater more acidic (Harvell *et al.*, 2007). This happens because of serious of reversible reactions as per Eq. (1). First, dissolved CO_2 gas will produce carbonic acid by reacting with seawater. Carbonic acid is a very weak acid, therefore it dissociates and produces hydrogen ions and bicarbonate ions. Furthermore, bicarbonate ions will also dissociate into hydrogen ions and carbonate ions. However, bicarbonate ions are more stable than carbonate ions in seawater. Therefore, dissolving CO_2 gas in the ocean will increase hydrogen ion concentration [H^+], and as a result, pH will reduce because, by definition, pH is –log10[H^+] (Doney *et al.*, 2009). Oceanic carbonate chemistry can be used to explain the sensitivity of the seawater pH to the adding CO_2 (Caldeira, 1999).

$$CO_2(\text{atm}) \leftrightarrow CO_2(\text{aqs}) + H_2O \leftrightarrow H_2CO_3 \leftrightarrow H^+ + HCO_3^- \leftrightarrow 2H^+ + CO_3^{2-} \tag{1}$$

3.1.1 Oceanic Carbonate Chemistry

There are two main factors that control the carbonate chemistry in the ocean. They are atmospheric carbon dioxide partial pressure (pCO_2) and ocean carbonate-ion concentration [CO_3^{2-}] (Caldeira, 1999). In (Zeebe, 2012), three definitions have been described under oceanic carbonate chemistry which were also used in other literature to explain the pH sensitivity to the CO_2 absorption. The terms are total dissolved inorganic carbon (TCO_2), total alkalinity (TA), $CaCO_3$ saturation state of seawater (Ω) which are explained in Eq. (2), Eq. (3) and Eq. (4) respectively.

$$TCO_2 = CO_2(aqs) + HCO_3^- + CO_3^{2-} \tag{2}$$

$$\text{TA} = [HCO_3^-] + 2[CO_3^{2-}] + [B(OH)_4^-] + [OH^-] - [H^+] + minor\ compounds \tag{3}$$

$$\Omega = \frac{[Ca^{2+}] \times [CO_3^{2-}]}{K_{sp}^*} \tag{4}$$

K_{sp}^* is the solubility product of calcite or aragonite.

According to Eq. (2), total dissolved inorganic carbon is defined as the sum of the inorganic carbons exists in the ocean. There are mainly three inorganic carbon forms that result from dissolving CO_2 in the seawater. They are free aqueous carbon dioxide (CO_2 (as)), bicarbonate ion (HCO_3^-), and carbonate ion (CO_3^{2-}). As previously mentioned, because of the high stability of bicarbonate ions in seawater, more than 85% of inorganic carbon is dissolved in the ocean as bicarbonate ions.

3.1.2 Drivers of CO_2 Emission

Gatusso et al (2014) have mentioned burning fossil fuel, cement manufacturing, and change in land use as the three main drivers of CO_2 emission. In 2012, burning fossil fuels was responsible for about 90% of global CO_2 emissions (Billé *et al.*, 2013). Ken Caldeira & Wickett (2003) have studied the effect of CO_2 emission from burning fossil fuel on the oceanic pH. According to their predictions, CO_2 emission will exceed 1900 ppm at around 2300. Also, the pH in the surface ocean will decrease by 0.7 as shown in Figure 1.

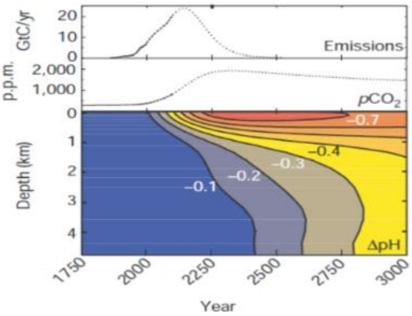

Figure 1: Atmospheric release of CO_2 from the burning of fossil fuels may give rise to a marked increase in ocean acidity. CO_2 emissions, historical atmospheric CO_2 levels (solid lines), and predicted CO_2 concentrations (dashed lines) from this emissions scenario, together with changes in ocean pH based on horizontally averaged chemistry (Caldeira and Wickett, 2003).

3.1.3 Sensitivity of Sea Water pH to Adding CO_2

This can be explained by the carbonate chemistry of seawater. K. Caldeira (1999) has predicted pH variation with pCO_2 using Eq.(5), with two assumptions that carbonate-ion concentration is constant and total dissolved inorganic carbon concentration is constant.

$$pCO_2 = \frac{K_H\,[H^+]^2[CO_3^{2-}]}{K_1 K_2} \tag{5}$$

K_H is Henry's law constant for CO_2, K_1 and K_2 are the first and second dissociation constants for carbonic acid respectively.

As shown in Figure 2, oceanic pH is more sensitive to atmospheric CO_2 pressure under constant carbonate-ion concentration (K. Caldeira, 1999).

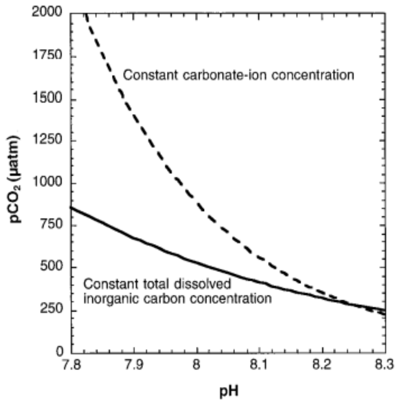

Figure 2: Variation of pH with pCO_2, Solid line – pH vs pCO_2 under constant total dissolved inorganic carbon concentration, Dash line - pH vs pCO_2 under constant carbonate-ion concentration, both curves assumed that pH = 8.25 at 280 ppm (preindustrial pCO_2)(Caldeira, 1999).

3.2 Coral Degradation

Coral reef systems are one of the most negatively affected ecosystems by ocean acidification. The calcification process of reef-building corals is reduced by ocean acidification through increased acidity of seawater as illustrated in Figure 3. Moreover, ocean acidification reduces the $CaCO_3$ saturation state in seawater (Ω) (Spalding and Brown, 2015).

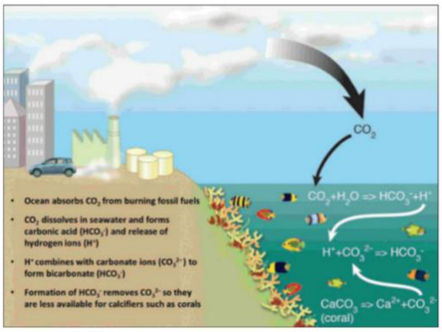

Figure 3: Linkages between the buildup of atmospheric CO_2 from burning fossil fuels and the slowing of coral calcification due to ocean acidification. Atmospheric CO_2 is taken up by the oceans and results in a decrease in $CO_3{}^{2-}$ concentration, making $CO_3{}^{2-}$ unavailable to marine calcifies like corals (McLeod *et al.*, 2013).

3.2.1 Coral Calcification Process

Coral calcification is a slow process where reef-building corals form skeletons of calcium carbonate (Allemand and Osborn, 2019). Normally, the calcification rate is 4kg of $CaCO_3$ per year (Smith and Kinsey, 1976). As mentioned by (Courtney *et al.*, 2017), several environmental factors affect to the coral calcification process such as seawater temperature, seawater carbonate chemistry, light and depth, food availability, nutrients, water flow rates, sedimentation, and competition. According to the study on hermatypic coral *Acropora eurystoma* by Schneider & Erez (2006), the calcification of coral is mainly sensitive to the Carbonate ion (CO_3^{2-}) concentration in seawater.

3.2.2 Effect of Ocean Acidification on Coral Calcification Process

Schneider & Erez (2006) have found that 20% of calcification reduction occurred when the atmospheric pressure of CO_2 increases from the preindustrial level (pCO_2= 280ppm) to 360 ppm. Moreover, Korndner et al (2018) have studied the calcification of shallow water reef-building reefs and reported that coral calcification is reduced by 20% when pCO_2 exceeds 700ppm and temperature increases by 3 ℃. Also, they have identified the threshold of pCO_2 to maintain the existing rate of calcification rates of shallow water corals is 700ppm.

Calcification and dissolution rate are also determined by the $CaCO_3$ saturation state of seawater (Ω) as per Eq. (4). The major soluble forms of $CaCO_3$ in seawater are known as calcite and aragonite (Zeebe, 2012). Therefore, both calcite and aragonite saturation states affect to the coral calcification process. Fabry et al (2008) have stated that the $CaCO_3$ saturation state of seawater (Ω) has a major impact on calcification compared to pH, TCO_2, and TA. $CaCO_3$ saturation state of seawater (Ω) > 1 implies a supersaturation condition where coral calcification is favorable and (Ω) < 1 implies an undersaturation condition where coral skeleton dissolution is favorable (Doney *et al.*, 2009). Many researchers have studied the variation of the $CaCO_3$ saturation state of seawater (Ω) with increased atmospheric CO_2 pressure to explain ocean acidification impacts on coral calcification. Fabry et al (2008) have interpreted the behavior of projected aragonite saturation state in surface seawater for the years 1765, 1994, 2050, and 2100. According to their results, under the IPCC IS92a "business-as-usual" CO_2 emission scenario, portions of the Subarctic North Pacific and all the Southern Ocean south of ~ 60°S will become under-saturated concerning aragonite. In (Gattuso *et al.*, 1998), it was observed that the calcification rate of the zooxanthellate coral *Stylophora pistillata* does not have a considerable effect on aragonite saturation levels corresponding to the last glacial-interglacial cycle (Refer Figure 4).

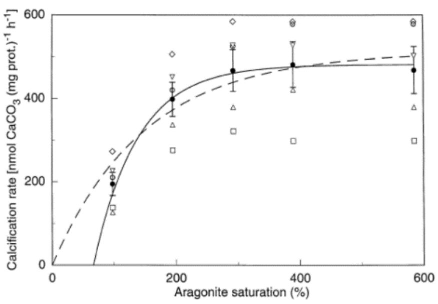

Figure 4 : Variation of Calcification Rate with Aragonite Saturation (Gattuso *et al.*, 1998).

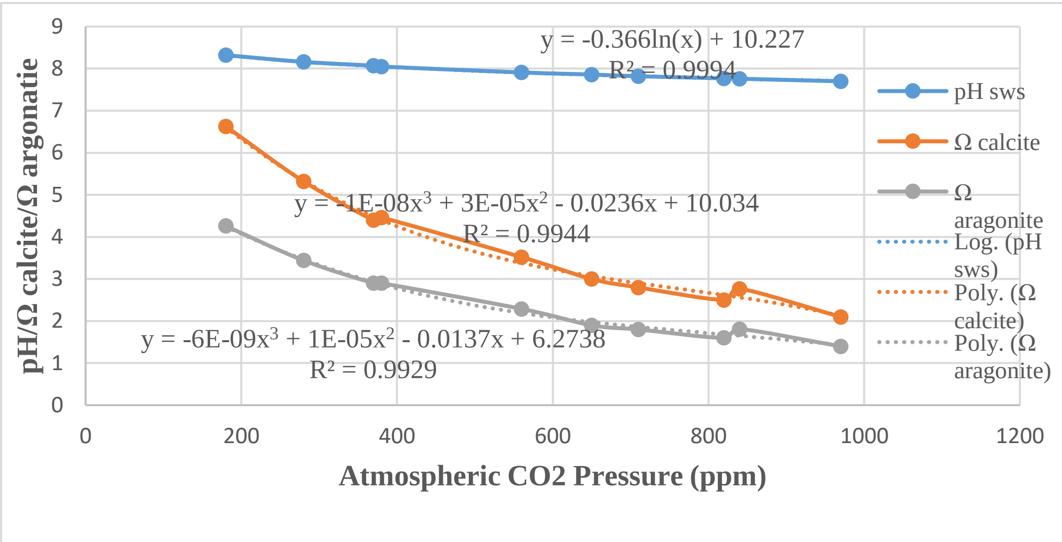

Figure 5: Variation of Surface Seawater pH and $CaCO_3$ Saturation State (Ω) with Atmospheric CO_2 Pressure: Data collected from (Fabry *et al.*, 2008),(Caldeira and Wickett, 2005).

Figure 5 implies that the $CaCO_3$ saturation state decreases with the atmospheric pressure of CO_2. As discussed in section 3.1, dissolving CO_2 in seawater reduces CO_3^{2-} concentration. As a result, it will reduce the $CaCO_3$ saturation state according to Eq. (4). Therefore, the variation of Figure 5 is obvious. Considering all the reasons it can be concluded that ocean acidification has negative impacts on coral calcification such as calcification inhibition, reduction of calcification rate, and dissolution of coral skeleton.

3.2.3 Warm-Water (Tropical) Coral Degradation

The reefs located near the equator within 30 latitudes belong to the category of warm water reefs (tropical coral reefs) which provide vital ecosystem services to human society(Spalding and Brown, 2015). However, most of the corals have been threatened by human activities and climate changes Cooper *et al* (2008), have found that calcification rate and linear extension in massive Porites from Great Barrier Reef (GBR) were reduced by 1.29 % yr^{-1} and 1.02% yr^{-1} respectively. However, due to the lack of data such as the $CaCO_3$ saturation state of GBR, it cannot be concluded that the above observations were directly affected by ocean acidification. De'Ath et al (2012) have discovered that the coral cover of GBR has declined by 0.53%yr^{-1} through inspections of 214 reefs from 1985-2012. According to their study, the major reason for the damage is tropical cyclones. Agreeing to the findings of (Bruno and Selig, 2007) coral cover in GBR slightly increased between 1997-2004. This is a contrast observation with previous discoveries about GBR. Moreover, McFarland (2021) has predicted that the combustion of coal from the new Carmichael Coal Mine in Queensland will cause extreme impacts on GBR through ocean acidification and ocean warming in the future.

3.2.4 Cold-Water (Deep) Coral Degradation

Cold-water reefs circulate the organic carbon in deep sea water while acting as a hotspot for biodiversity in the deep ocean (Cathalot *et al.*, 2015). Similar to tropical reefs, cold water reefs are also endangered by human activities such as gas exploration, seafloor installations, and accidental oil spilling (Fisher *et al.*, 2014). Nevertheless, cold water reefs are more vulnerable than tropical reefs when it comes to climate change (Cathalot *et al.*, 2015), especially ocean acidification (Ken Caldeira & Wickett, 2003). With the increase of the ocean depth, the $CaCO_3$ saturation state of seawater changes from (Ω) > 1 to

(Ω) < 1, because K^*_{sp} increases with the pressure. Therefore, corals in the deep ocean are more like to dissolve as they live in an undersaturated condition (Zeebe, 2012).

Several studies have focused on *Lophelia pertusa* which is a dominant reef-building cold water reef and its responses to ocean acidification. The calcification of cold-water coral *Lophelia pertusa* was reduced by 55% when pH was 46% lower than the ambient seawater value *and* still could maintain its calcification process even at a $CaCO_3$ saturation state close to 1(Maier *et al.*, 2009). The effect of exposure time of CO_2 on cold-coral calcification was studied by using *Lophelia pertusa* (Form and Riebesell, 2012). For 1 week of exposure time, calcification was reduced by 26–29% because of a 0.1 pH decline. But, for 6 months of CO_2 exposure, coral adapted to acidified conditions and at the same time indicated a slight rise in calcification rate. In contrast, Hennige et al (2014) have identified that there was no change in calcification in *Lophelia pertusa* as a short-term response to ocean acidification. The experiment was conducted for 3 weeks (21 days) under 750ppm CO_2 concentration.

4. Proposed solutions and studies

4.1 Mitigation

Workman et al (2011) have discussed five methods for CO_2 removal from the atmosphere artificial trees, soda/lime process, augmented ocean disposal process, biochar, and biomass Energy with Carbon Capture and Storage (BECCS). Artificial trees use a chemical absorbent to absorb CO_2 directly from the atmosphere. It is recommended to implement close to CO_2 source to gain effective removal (Workman *et al.*, 2011). Although lime production removes CO_2 from the atmosphere, it causes coral mining which has become a major threat for corals, especially hard corals. For example, coral mining for lime production is identified as a major threat to corals in Sri Lanka (Rajasuriya and White, 1995). The augmented ocean disposal process is the process in which the ocean absorbs excess CO_2 in the atmosphere. Without hesitation, the augmented ocean disposal process can be rejected as this is the main reason for ocean acidification. Efficient methods of biochar and BECCS mainly depend on biomass availability (Workman *et al.*, 2011). However, using 3rd generation biomasses (micro/macroalgae) will help overcome this problem (Yeong *et al.*, 2018). In addition to the above methods, ocean fertilization using naturally scarce nutrients will increase the ability to absorb atmospheric CO_2 by the ocean and as a result, it reduces atmospheric CO_2 concentration. Due to the high uncertainties of this method, it is not practiced except for necessary scientific research (Billé *et al.*, 2013).

There are several global protocols and agreements that have been implemented to reduce the emission of greenhouse gases by the United Nations Framework Convention on Climate Change (UNFCCC) since 1992. According to (Lebrec *et al.*, 2019)**, the** Kyoto Protocol is the most substantial emission trading system that applies to the Pacific Basin. However, it is uncertain about the effectiveness of this protocol as several developed countries that are identified as top CO_2 emitters have decided not to take part in this (Billé *et al.*, 2013). Therefore, it is essential to build up protocols specific to CO_2 emission to obtain effective mitigation of ocean acidification (Harrould-Kolieb and Herr, 2012; Gattuso *et al.*, 2015).

Among other solutions discussed here, mitigation of GHG gas emissions including CO_2 is identified as the best practice because of its economic and social feasibility compared to other methods (Hoegh-Guldberg and F. Bruno, 2010) (Refer Figure 6).

4.2 Adaptation

In here, it is intended to mitigate ocean acidification by adapting human lifestyle to climate change. For instance, creating artificial reefs, and underwater marine museums has shown progress in sustainable tourism.(Billé *et al.*, 2013).Also, strengthening intra/international collaboration helps to monitor coral reefs' health and also to organize educational programs (Allemand and Osborn, 2019). A very good example is the United Nations Sustainable Development Goal (SDG) 14.3 where the UN created nearly 40 voluntary groups all around the world to find solutions for ocean acidification mitigation (Lebrec *et al.*, 2019).

4.3 Protection

Reducing chronic stresses such as coral disease, overfishing, and coastal pollution will increase the resilience of coral reefs towards climate change.(Carilli *et al.*, 2009). In (McLeod *et al.*, 2013), they have emphasized the need for conservation management of seawater carbonate chemistry and more information about marine sensitivity towards ocean acidification for the protection of coral reefs from ocean acidification. Establishing marine protected areas where there is high species diversity is another way to improve the resilience of coral reefs towards global change. It has been reviewed that ecosystems that have high diversity show more resilience to climate change (Folke *et al.*, 2004). However, its effectiveness is still questionable as more than 90% of the reef area in GBR has undergone coral bleaching during 2015-2016 (Allemand and Osborn, 2019).

4.4 Repair and Restore

4.4.1. Repair Acidified Sea

The main objective here is to reduce acidity in the sea. This can be primarily achieved by reducing the dissolving CO_2 concentration in seawater. A successful method is promoting natural "CO_2 sinks" such as seagrasses and mangroves (Allemand and Osborn, 2019). A novel method of CO_2 extraction from seawater using bipolar membrane electrodialysis has been proposed by Eisaman et al (2012). This method is more efficient than previously used methods as it has 59% extraction efficiency through energy consumption of 242 kJ mol^{-1} (CO_2). The addition of alkaline substances such as calcium oxide, and alkaline rocks will increase the alkalinity in seawater thus it will increase the pH in seawater (Billé *et al.*, 2013).

M-Einarsson et al (2020) have reviewed several methods of restoring degraded corals. They are direct transplantation, coral gardening, micro-fragmentation, genetic diversity in asexual propagation, larval enhancement, etc.

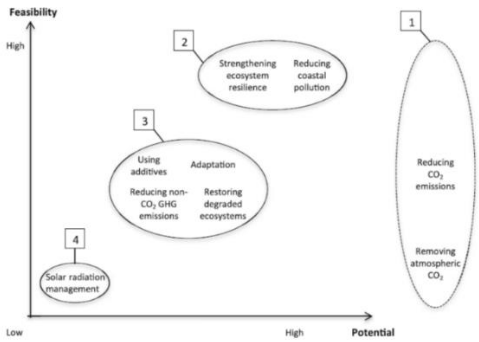

Figure 7: Comparison of Potential and Feasibility of Proposed Solutions (Billé *et al.*, 2013).

5. Conclusions

This review reaffirms four key points considered in previous studies.

1. There are several studies based on the impacts of climate change on coral reefs. Yet most of those studies or experiments have focused on either ocean acidification (atmospheric CO_2 concentration) or ocean warming (sea water temperature) individually. The knowledge about the combined effect of ocean acidification and ocean warming on coral reefs which is the real case is still lacking.

2. Cold-water coral reefs are more sensitive to pH changes than warm-water coral reefs. However, most pH reductions happen around the sea surface where warm water coral reefs exist. Therefore, it can be concluded that both types of coral are at risk of ocean acidification.

3. Due to practical difficulties, experiments about cold water reefs (deep water reefs) are limited. Therefore, understanding of cold-water reefs relating to ocean acidification is also constrained.

4. Specified protocols are needed which mainly focus on reducing CO_2 emissions to mitigate ocean acidification effectively.

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SUSTAINABLE CONSTRUCTION AND GREEN BUILDING TECHNIQUES

ICSBE 2023-3

SIMULATION OF TIME-DEPENDENT BEHAVIOUR OF RESTRAINED RC ELEMENTS

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Abstract: The time-dependent behaviour of reinforced concrete occurs mainly due to the creep and shrinkage of the concrete material and is crucial in restrained structures, particularly for its serviceability performance. Typically, RC structures are designed for such effects and oversimplified rules stipulated in codes of practice. However, both creep and shrinkage are non-linear behaviours. Also, the shrinkage of concrete in the presence of reinforcement is complicated. This study first explored commonly used creep/shrinkage models. Second, using an available experimental result, the potential of those creep/shrinkage models to capture the time-dependent behaviour of reinforced concrete walls was assessed via a finite element (FE) study. It was identified that the Eurocode 2 (EC2) model was promising for both modelling normal strength applications and high strength applications. Subsequently, the numerical modelling was extended towards a case study where undesirable cracking was reported in beams and slabs of a multi-rise building. It was identified that most of the observed cracks were simulated reasonably by the FE model, and the model showed that the time-dependent behaviour was the main cause of the cracking of the structure. It was also highlighted that some of the cracks were due to design overlooks, and some were due to shortcomings in the design guidelines.

Keywords: Creep; Shrinkage; Time-dependent Behaviour; Crack; Reinforced Concrete

1. Introduction

Concrete is subjected to non-structural effects of creep and shrinkage over long-term service. These non-structural responses lead to undesirable deflections in reinforced concrete (RC) structures, and under retrained conditions, to considerable cracking. RC structures are designed for such consequences through simplified rules outlined in codes of practice. The effect of creep and shrinkage have been incorporated for design guidelines in models such as ACI 209(Rhodes et al., 1982), EC2 (BS EN 1992-1-1:2004) and CEB fib MC 10 (Ernst & Sohn, 2013). However, with the presence of reinforcement in concrete structures, accurate analytical estimation of creep and shrinkage becomes complicated(Shariff and Menon, 2020).

The objectives of the study were identifying appropriate creep/shrinkage models for concrete that can incorporate the presence of reinforcement via available experimental results, validating the numerical modelling potential of the time-dependent behaviour of reinforced concrete, exploring the influence of creep/shrinkage towards the behaviour of RC beams/slabs through numerical analysis.

The significance of the research is identifying the main reasons for cracks in reinforced concrete structures. In the methodology of the research, first creep/shrinkage models were explored and differences between models were identified. Additionally, functions for creep compliance, creep coefficient, and shrinkage strain were found for a variety of models, including ACI 209, EC2 and CEB fib MC 10. Then, experiments on shrinkage and creep were examined and the behaviour of experiments was predicted analytically for experiments. Then analytical variation and experimental variation were compared, and an appropriate model was chosen since it exhibited approximately identical variation to experimental variation. Next, Midas FEA software was used for FE modelling and FE predictions were validated for existing results on wall behaviour, beam behaviour, and slab behaviour and the potential of the software to capture such time-dependent behaviour was verified. After verifying the potential of the software, 3D FE modelling was created for the RC slab which had shrinkage issues.

2. Literature Review

2.1 Existing creep/shrinkage models

The basic models for creep and shrinkage are developed empirically based on long-term tests carried out on plain concrete cylinders and prisms of small size and validated with experiments on RC columns(Shariff and Menon, 2018). Some of the existing creep and shrinkage models are ACI 209, EC2 and CEB fib MC 10.

Time–rate functions for both creep and shrinkage strains are described using hyperbolic functions in the ACI 209 model. In the EC2 model, shrinkage strain is expressed as a combination of autogenous and drying shrinkage. The time-rate functions for creep, autogenous shrinkage and drying shrinkage are the power law function, exponential function, and hyperbolic function respectively. The time rate functions of the CEB fib MC 10 model for basic creep, drying creep, autogenous shrinkage, and drying shrinkage are logarithmic function, hyperbolic function, exponential function, and hyperbolic function respectively(Shariff and Menon, 2020).

2.2 Experimentation and analytical prediction of creep/shrinkage behaviour for walls

Shariff & Menon, 2020 experimented on four large-scale wall specimens, subjected to axial compressive load under ambient environmental conditions, for a period of 1 year to study the concrete strength on the development of creep and shrinkage strains. Both high-strength (HS) and normal-strength (NS) concrete were utilized. Table 1 shows the concrete mixture specification of high-strength and normal-strength concrete.

Table 1: Concrete mixture specification, kg/m3

	Normal Strength	**High Strength**
Cement	404	450
Micro silica	—	30
Fly ash (Class F)	—	110
Water	192	168
20 mm aggregate	—	697
12.5 mm aggregate	828	376
Sand	953	657
Admixture PCE	—	3.54

The reinforcement details of the specimens are shown in Figure 1.

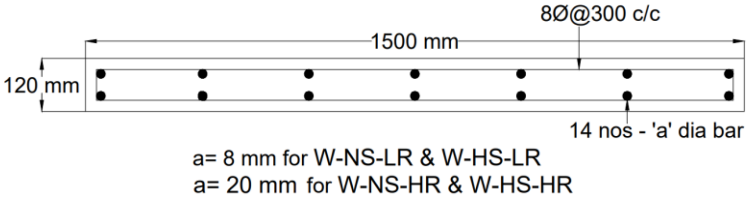

Figure 1: Reinforcement details of the wall specimens.

The percentage of reinforcement to the concrete area for light reinforcement was 0.4% and 2.4% for heavy reinforcement and the four large-scale wall specimens were normal strength light reinforcement wall (W-NS-LR), normal strength heavy reinforcement wall (W-NS-HR), high strength light reinforcement wall (W-HS-LR), and high strength heavy reinforcement wall (W-HS-HR).

2.2.1. Analytical Prediction of Wall Experimental Behavior

Time-dependent strains in RC walls were analytically predicted using ACI 209, EC2, and CEB fib MC 10 models in this investigation. Figure 2 shows the analytical and experimental variation of creep/ shrinkage strain for the NS LR wall.

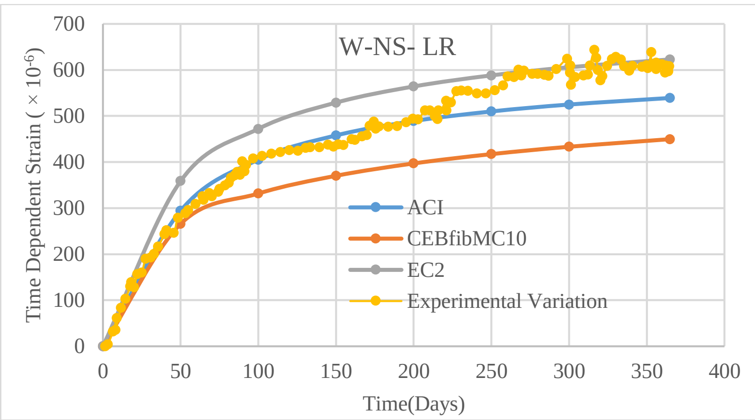

Figure 2 - Analytical and experimental variation of creep/ shrinkage strain for NS LR wall.

The mean value of $(\varepsilon_{cs(theo)})/(\varepsilon_{cs(exp)})$ was examined to compare analytical variation and experimental variation. Table 2 shows the mean values of $(\varepsilon_{cs(theo)})/(\varepsilon_{cs(exp)})$ for NS LR, HS LR, NS HR and HS-HR walls.

Table 2 - Mean values of $(\varepsilon_{cs(theo)})/(\varepsilon_{cs(exp)})$ for NS LR , HS LR, NS HR and HS HR walls

Model	Mean $(\boldsymbol{\varepsilon_{cs(theo)}})/(\boldsymbol{\varepsilon_{cs(exp)}})$			
	W-NS LR	W-HS LR	W-NS HR	W-HS-HR
ACI 209	0.97	0.99	1.06	1.56
CEB fib MC10	0.81	0.78	0.81	1.21
EC2	1.14	1.07	1.34	1.69

The ACI 209 model exhibited enhanced accuracy in predicting creep and shrinkage strain for the W-NS-LR wall, as the mean value of $(\varepsilon_{cs(theo)})/(\varepsilon_{cs(exp)})$ was close to 1.The ACI 209 model predicted creep and shrinkage correctly for the W-HS-LR wall, as the mean value of $(\varepsilon_{cs(theo)})/\ (\varepsilon_{cs(exp)})$ was approximately to 1.

When strengthening concrete grade, analytical behaviour was correctly estimated using the ACI 209 model. Therefore ACI 209 model could be used to compare the effect of compressive strength on time-dependent behaviour.

When comparing the mean value of $(\varepsilon_{cs(theo)})/(\varepsilon_{cs(exp)})$ for the W-NS-HR wall, which was almost 1 for the ACI 209 model. When enhancing the reinforcement percentage, analytical behaviour was estimated correctly using the ACI 209 model. Therefore ACI 209 model could be used to compare the effect of reinforcement percentage for time-dependent behaviour.

As the mean value of $(\varepsilon_{cs(theo)})/\ (\varepsilon_{cs(exp)})$ for CEB fib MC 10 model was near 1 for the W-HS-HR wall, it predicted creep and shrinkage strain correctly. When improving reinforcement percentage and concrete strength, analytical behaviour was estimated correctly using the CEB fib MC 10 model. Therefore, the CEB fib MC 10 model could be used to predict the effect of both concrete strength and reinforcement for time-dependent behaviour.

2.3. Experimentation and analytical prediction for beam

Daud et al, 2015 experimented on beam deflection. Mid-span deflection, creep coefficient, and shrinkage strains were monitored for 90 days.

In this investigation, EC 2, ACI 209 and CEB fib MC 10 models were used to predict the time-dependent deflection of the beam. Figure 3 shows the variation of developed deflection with time.

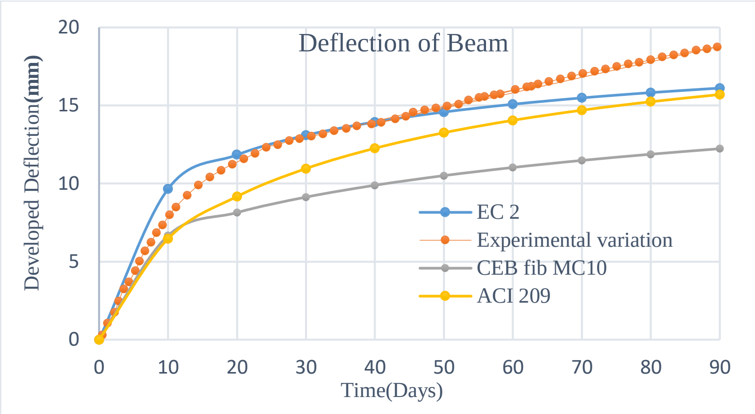

Figure 3: Variation of developed deflection with time.

Table 3 shows the mean values of $(\varepsilon_{cs(theo)})/(\varepsilon_{cs(exp)})$ for beam.

Table 3 - Mean values of $(\varepsilon_{cs(theo)})/(\varepsilon_{cs(exp)})$ for beam.

Model	The mean value of $(\boldsymbol{\varepsilon_{cs(theo)}})/(\boldsymbol{\varepsilon_{cs(exp)}})$
ACI 209	0.85
CEB fib MC 10	0.70
EC2	0.98

As the mean value of the analytical to experimental deflection ratio of EC 2 was approximately equal to 1, it predicted beam deflection accurately.

3. Numerical Modelling

3.1 Numerical Modelling of Wall

MIDAS FEA was used to predict the numerical behaviour of reinforced concrete walls that were experimented by Shariff & Menon, 2020. Table 4 shows the details of the input parameters that were used for the numerical modelling of the wall.

Table 4 - Details of input parameters for numerical modelling of the wall.

Parameter	W-NS LR	W-HS LR	W-NS HR	W-HS-HR
Cylinder compressive strength at 28 days (MPa)	36	51.7	36	51.7
Axial Load (kN)	720	1000	720	1000
Elastic Modulus at 28 days (MPa)	29764	41641	29764	41641
Cement Content (kg/m3)	404	450	404	450
Fine aggregate percentage (%)	53.51	37.98	53.51	37.98
Reinforcement percentage (%)	0.4	0.4	2.4	2.4
Notional size (mm)	111.11			
Age at shrinkage (days)	7			

Figure 4 shows the numerical modelling of the reinforced concrete wall.

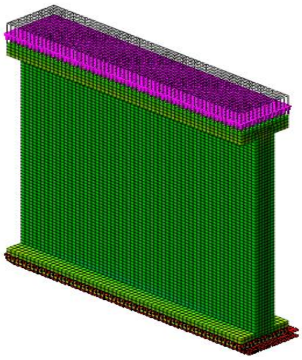

Figure 4: Numerical modelling of reinforced concrete wall.

The wall was modelled using 25 mm 8-node iso-parametric solid brick elements and reinforcements were modelled using 1D reinforcement mesh. In MIDAS FEA reinforcement element can be used as an embedded element in both 2D and solid elements. Creep/ Shrinkage models were defined to predict the time-dependent behaviour of RC walls. The model type of concrete was considered elastic, as the behaviour of concrete material is almost linear, over this load intensity. ACI 209, CEB fib MC 10, and EC 2 models were defined to obtain the variation of creep coefficient, shrinkage strain, compressive strength, tensile strength, and elastic modulus with time. The construction stage was defined to indicate the changes in the configuration of the wall, boundary condition, and loading with time.

3.2 Numerical modelling of lightweight concrete slab

The simply supported slab that was tested by Vakhshouri et al., 2018, was numerically modelled using Midas FEA software. In this experiment, the effect of stress on the time-dependent deflection of slabs was investigated. Table 5 shows the details of the input parameters that were used for the numerical modelling of a lightweight concrete slab.

Table 5 - Details of input parameters for numerical modelling of lightweight concrete slab.

Parameter	Value
Compressive strength at 28 days	31 MPa
Applied Load	31.75 kN/m2
Elastic Modulus at 28 days	31938 MPa
Cement Content	500 kg/m3
Notional size	114.8 mm
Age at shrinkage	14 days
Relative humidity	50%

Figure 5 shows the numerical modelling of the slab.

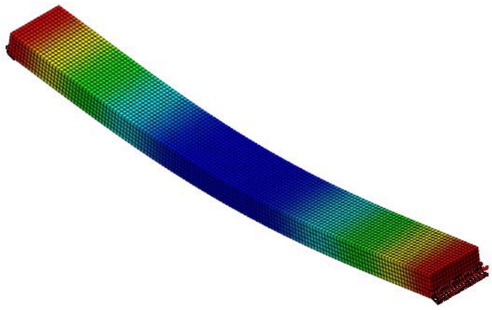

Figure 5 - Numerical modelling of slab.

The slab was modelled using 8-node iso-parametric solid brick elements and reinforcements were modelled using 1D reinforcement mesh. The concrete model was regarded as elastic since the behaviour of the concrete material remains predominantly linear under this level of loading. Creep coefficient, shrinkage strain, and compressive strength were defined using user-defined ACI 209, CEB fib MC 10, and EC 2.

4. Results and Discussion

4.1 Results of Wall Modelling

Creep and shrinkage strains were obtained from numerical modelling and variations of strains between experimental and numerical were monitored. Figure 6 shows the numerical and experimental creep/shrinkage variation of the NS LR wall.

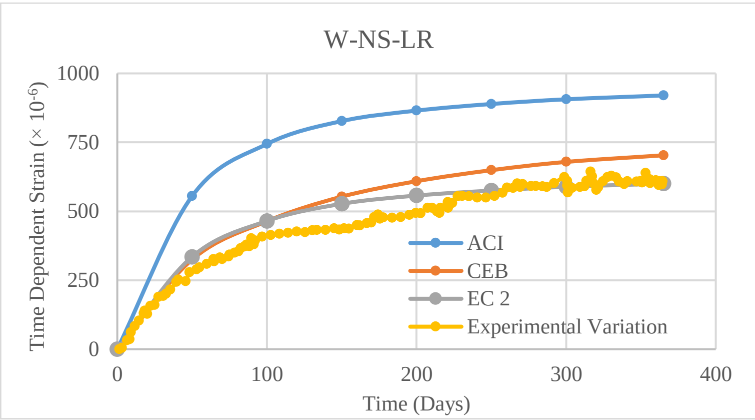

Figure 6 - Comparison of numerical and experimental time-dependent strain (NS LR).

Numerical variation and experimental variation were compared to validate numerical modelling. The numerical modelling potential of time-dependent behaviour was checked in the validating process. If Midas FEA software could predict numerical variation close to the experimental variation, the software has the potential to predict time-dependent behaviour.

The mean value of $(\varepsilon_{cs(num)})/\ (\varepsilon_{cs(exp)})$ was considered to compare numerical variation and experimental variation. Table 6 shows the mean values of $(\varepsilon_{cs(num)})/\ (\varepsilon_{cs(exp)})$ for NS LR, HS LR, NS HR and HS HR walls.

Table 6 - Mean values of $(\varepsilon_{cs(num)})/(\varepsilon_{cs(exp)})$ for NS LR, HS LR ,NS-HR and HS HR walls

Model	Mean $(\boldsymbol{\varepsilon_{cs(num)}})/(\boldsymbol{\varepsilon_{cs(exp)}})$			
	W-NS LR	W-HS LR	W-NS HR	W-HS-HR
ACI 209	1.71	1.90	1.79	1.81
CEB fib MC10	1.17	1.25	1.23	1.68
EC2	1.09	1.18	1.18	1.48

The EC 2 model was predicted creep and shrinkage strain accurately, as the mean value of $(\varepsilon_{cs(num)})/(\varepsilon_{cs(exp)})$ was approximately 1 for NS LR wall. Since numerical variation was close to the experimental variation, it was identified that Midas FEA software had the potential to predict time-dependent behaviour.

The mean values of $(\varepsilon_{cs(num)})/(\varepsilon_{cs(exp)})$ for W-HS-LR and W-NS-HR were almost 1 for EC 2. Therefore, Midas FEA software had the potential to predict time-dependent behaviour. However, EC2 has not predicted very close variation between numerical and experimental for the HS HR wall. EC 2 predicted time-dependent strains correctly for both normal strength and high strength applications. In plane time dependent deformation of reinforced concrete walls was evaluated through numerical modelling.

4.2 Results of Lightweight Slab Modelling

Figure 7 shows the variation of deflection with time for the lightweight slab.

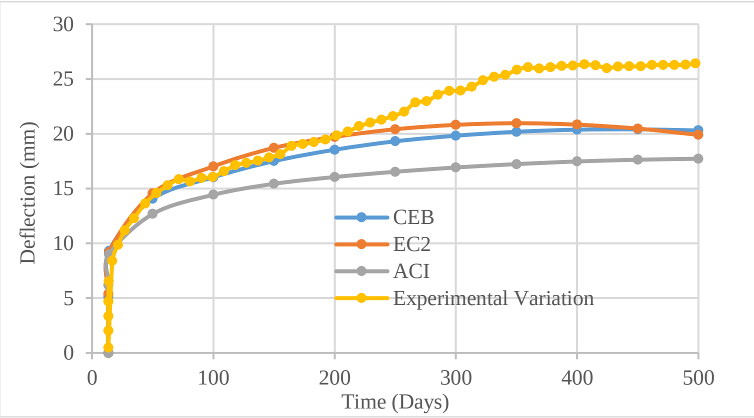

Figure 7 - Variation of deflection with time for lightweight slab.

Table 7 shows the mean values of $(\varepsilon_{cs(num)})/(\varepsilon_{cs(exp)})$ for the slab.

Table 7 - Mean values of $(\varepsilon_{cs(num)})/(\varepsilon_{cs(exp)})$ for lightweight slab

Model	The mean value of $(\boldsymbol{\varepsilon_{cs(num)}})/(\boldsymbol{\varepsilon_{cs(exp)}})$
ACI 209	0.78
CEB fib MC 10	0.86

EC 2	0.90

The mean value of numerically predicted experimental deflection was closer to 1 for the EC 2 model. Therefore, Midas FEA had the potential to predict time-dependent behaviour. The time-dependent defection of flexure element was examined through numerical modelling.

5. Case Study

The findings of the numerical study could be applied in the case study. The beams and slabs in the basement of a multi-storey building at Peradeniya exhibited considerable cracking after one month of construction as depicted in Figure 8.

Figure 8: Crack patterns of the beam.

The crack locations of the basement slab are bounded by red rectangles in Figure 9. Moreover, all cracks were situated middle area of the B6 beams.

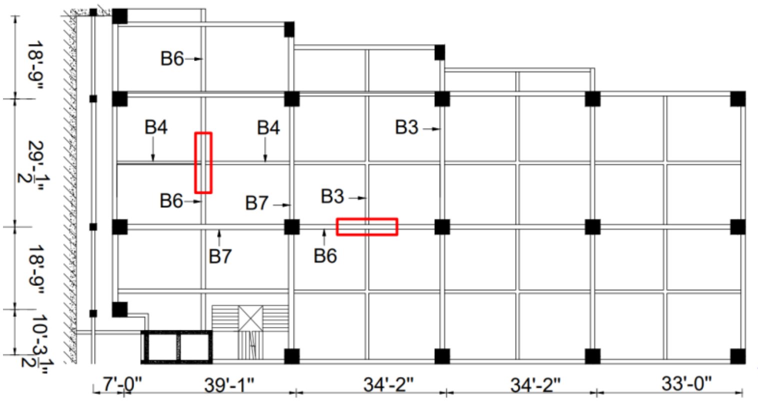

Figure 9: Crack locations of the basement slab.

As there were cracks in the middle area of the beam, these cracks were identified as shrinkage cracks. Therefore, the main cause of the distress was identified to be the restrained shrinkage due to drying shrinkage of concrete, supplemented with bending due to self-weight.

Table 8 shows the details of the input parameters that were used for the numerical modelling of the slab.

Table 8: Details of input parameters

Parameter	value
Concrete Grade	C25/30
Slab Thickness	150 mm
Permanent Load (self-weight + floor finish)	4.75 kN/m2
Variable Load	4.0 kN/m2
Relative humidity	84 %
Notional size	150.55 mm
Age at shrinkage	7 days
Age of loading	14 days

The area bounded by the red polygon of the basement slab drawing, which is shown in Figure 10, was used for numerical modelling.

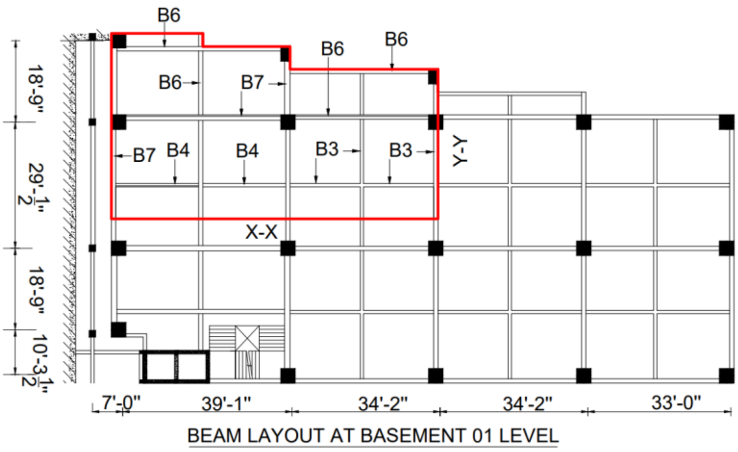

Figure 10: Area of the slab that was used for numerical modelling.

A quarter of the slab was taken to reduce the computational effort of the analysis.

5.1 Method of Numerical Modelling of Slab

Slabs, beams, and columns were modelled using 100 mm 8-node isoperimetric brick elements. Reinforcements were modelled using 1D reinforcement mesh. Concrete was considered an elastic material to activate creep and shrinkage functions. Boundary conditions of the base of columns were pin connected. Displacement was restrained along the perpendicular direction of the cut surface of the slab. Cracks were observed in the structure that was only under self-weight.

5.2 Results of Numerical Modelling of Slab

Figure 11 shows the variation of the stress of the slab and critical points of the beams in XX direction.

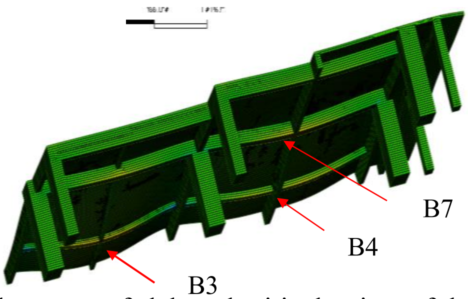

Figure 11 - Variation of the stress of slab and critical points of the beam in XX direction.

Figure 12 shows the variation of the stress of the slab and critical points of the beams in the YY direction.

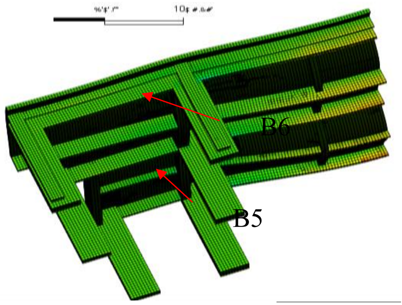

Figure 12 - Variation of the stress of the slab and critical points of the beams in the YY direction.

The crack width was calculated using the direct approach in EC2(BS EN 1992-1-1:2004). 28-day Crack width and long-term crack width are shown in Table 9.

Table 9 - 28 days crack width and long-term crack width

Beam	**28-day crack width (mm)**	**Long-term crack width (mm)**
B3	0.16	0.50
B4	0.08	0.23
B5	0.11	0.34
B6	0.13	0.39
B7	0.10	0.30

There were cracks in the B6 beam in 28 days as shown in figure 9. The numerical predicted crack location is similar to the actual crack location. In addition, the calculated crack width for the B6 beam in 28 days is 0.13 mm. Therefore, cracks at 28 days can be predicted using numerical modelling.

5.3 Cracked Assessment Based on EC 2

A cracked assessment based on EC 2 was carried out to check the reasons for the crack. The results of the serviceability limit state design for beams are shown in Table 10.

Table 10 - Results of serviceability limit state

Beam	Minimum reinforcement area requirement (mm2)	Provided reinforcement area (mm2)
B3	1935	603
B4	3638	1483
B5	4067	3171
B6	3087	3398
B7	5219	10713

According to the results provided reinforcement provisions were not adequate for B3, B4, and B5 beams. B3, B4, and B5 may be cracked due to design errors. Therefore, further code base crack width assessment could not be carried out due to design errors of the B3, B4 & B5 beams. However, provided reinforcement for B6 and B7 beams was enough according to the simplified approach. B6 and B7 beams were further studied to check the reason for the cracks in these beams. The crack width of B6 and B7 beams was calculated using a simplified approach and direct approach in EC2. Table 11 shows the calculated crack width in B6 and B7 beams using the simplified and direct approach.

Table 11 - Long-term crack width in B6 and B7 beams

Beam	Cracked width using simplified approach(mm)	Cracked width using a direct approach (mm)
B6	0.27	0.39
B7	0.20	0.30

The cracked width of the B7 beam using a direct approach is 0.3 mm. Therefore, the cracked width of the B7 beam was almost within the allowable limit. However, the cracked width of the B6 beam was 0.39 mm. Therefore, cracks could appear at the B6 beam as the crack width was beyond the allowable limit (0.3mm). Furthermore, the ultimate limit state design of the B6 beam was checked to identify the reason for the cracks.

The required reinforcement area for B6 was 1672 mm2 and the provided reinforcement area was 2945 mm2 in the ultimate limit state design. Therefore, the ultimate limit state design was satisfied for the B6 beam. Both ultimate and serviceability limit states were satisfied for the B6 beam. But calculated crack width using a direct approach was higher than 0.3 mm. Both shrinkage and load effect were considered when calculating crack width in a direct approach. The beam was divided into three parts to identify the variation of cracked width along the beam depth. The 28 days and long-term crack width at the middle and bottom of the B6 beam were obtained using a direct approach as shown in Table 12.

Table 12 - Crack width at the middle and bottom of the beam

	Crack spacing (mm)	28 days crack width (mm)	Long-term crack width (mm)
Middle	1627	0.23	0.59
Bottom	453	0.12	0.33

It is obvious from the measured results that the crack width was greater near the middle of the beam. When comparing the crack width at the middle and bottom of the beam, there was a higher crack width at the middle of the beam. As the reinforcement percentage was less valued at the middle of the beam, these cracks should be due to the shrinkage effect. Therefore, the main reason for cracks in the B6 beam was the shrinkage of concrete supplemented with bending due to self-weight.

6. Conclusions

In terms of the numerical prediction of in-plane time-dependent deformation of reinforced concrete (RC) walls, the EC2 time-dependent material model was found to be excellent in both normal-strength concrete applications and high-strength concrete applications. The case study showed that the main cause behind most of the observed cracks in flexure elements in an RC building was the time-dependent behaviour of concrete, which was not captured sufficiently over the code-based design. Since actual crack widths of the beams were not available in this case study, future study can be proposed for comparing actual crack widths and numerical crack widths. In this study only compression cracks were assessed. Thus, tension simulation can be carried out to compare crack width.

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TOWARDS SUSTAINABLE BUILDINGS: A REVIEW ON BUILDING MATERIAL SELECTION

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Abstract: With the ongoing global trend of urbanization, there has been a surge in demand for construction and building materials. However, this heightened demand has contributed significantly to environmental degradation through the extensive consumption of natural resources. In response to these environmental concerns, various novel materials are emerging as alternatives, emphasizing the critical nature of the selection process for building materials. Beyond the fundamental prerequisites of strength and durability, recent research has underscored additional considerations, encompassing environmental impacts, cost efficiency, and performance-related factors. Adopting a life cycle thinking approach better sustainable selection of materials over the long term. This article aims to comprehensively review the existing body of knowledge on methodologies for comparing and selecting building materials. Moreover, it aims to propose improved approaches that can enhance the efficiency of material selection, thereby contributing to the advancement of sustainable development. Material performance is influenced by a multitude of both quantitative and qualitative parameters. Experimental testing procedures, calculations, and computer simulations serve to quantify quantitative factors, while interviews, surveys, and on-site observations are employed to capture the qualitative preferences of end-users. In the combination of these diverse factors, Multi-Criteria Decision-Making (MCDM) methods play a pivotal role. Widely embraced techniques such as the Analytical Hierarchy Process (AHP) and the Technique for Order Preference by Similarities to Ideal Solution (TOPSIS) are frequently utilized for the systematic comparison and ranking of alternatives. The insights derived from this comprehensive review are poised to inspire researchers to propose innovative, industry-centric approaches for the discerning selection of the most suitable building materials for construction purposes.

Keywords: Sustainability; Life cycle thinking approach; Multi-criteria-decision making, Construction material selection

1. Introduction

The construction industry significantly impacts sustainability in both developed and developing nations (Heravi and Abdolvand, 2019). Around 40% of the world's energy usage and 40% to 50% of greenhouse gas emissions are a result of it (Aneesh, Shivaprasad, and Das, 2018; Heravi and Abdolvand, 2019). The construction industry heavily consumes natural resources such as raw materials, energy, and water (Heravi, Fathi, and Faeghi, 2017; Heravi and Abdolvand, 2019). Environmental risks and increased costs result from using natural resources that are depleted over time (Thevarajah *et al.*, 2020). Hence, the scarcity of natural resources is becoming a serious issue that results in high costs of construction (Thevarajah *et al.*, 2020). Furthermore, the construction of households and their operation-related costs create a significant impact on local and global economic development (Kulshreshtha *et al.*, 2020).

Natural or synthetic material that is being used for any construction is said to be a building material (Kubba, 2012a; Omer and Noguchi, 2020). A vast percentage of over 40% of the material applications are non-renewable (Asif, Muneer, and Kelley, 2007; Yahya and Boussabaine, 2010; Omer and Noguchi, 2020). Building materials contribute about 10% to 20% of the total building energy which will even increase with the development of the production of materials (Ramesh, Prakash, and Shukla, 2014; Ruuska and Häkkinen, 2014; Omer and Noguchi, 2020). During the lifetime of a building, the materials play a major role in energy consumption and contribute significantly to GHG emissions (Reza, Sadiq, and Hewage, 2011; Sagheb, Vafaeihosseini and Kumar, 2011; Hossaini *et al.*, 2014; Hong *et al.*, 2015; Yüksek, 2015; Omer and Noguchi, 2020).

Due to greater energy consumption and over-exploitation of natural resources, several newer materials are emerging as alternatives (Jayasinghe and Kamaladasa, 2007; Jayasinghe, 2011; Jayasinghe, Fonseka and Abeygunawardhene, 2016; Kariyawasam and Jayasinghe, 2016; Kota and Kalyana Rama, 2020). With the higher number of alternatives, building material selection has become a critical and complex task (Zhang *et al.*, 2019). The selection of the most desirable materials for a specific building will not be straightforward, it might need a multi-criteria-based decision-making framework that satisfies sustainable practices (Reza, Sadiq, and Hewage, 2011).

Building material selection plays an important role in the construction industry in paving the way for sustainable development (Kubba, 2012b, 2012a; Milagre Martins and Gonçalves, 2012; Omer and Noguchi, 2020). Sustainable building materials are introduced such that they consume lower energy in construction as well as in the operational stages (Kariyawasam and Jayasinghe, 2016). Recent researches state that up to 30% of total emissions during a building lifetime could be reduced by careful selection of alternative materials (Chen and Thomas Ng, 2016; Wheating, 2017). Material selection becomes important to reduce negative impacts on the climate as well as human health by providing a better indoor environment (Pedersen Zari, 2019). The selection of these alternative materials and the use most desirable materials for the building construction is significant in achieving sustainability. Improper selection of building materials could cause problems in terms of economy, functionality, and appearance that can even lead to a state in which it cannot be rectified easily (Alibaba and Özdeniz, 2004).

As the three primary approaches for material selection, Ashby et al. (2004) have identified a free searching strategy based on quantitative analysis, expert questionnaire strategy, and inductive reasoning and analogy strategy (Ashby *et al.*, 2004). Most of the studies have focused on quantitative performances and hence, qualitative aesthetic preferences of the end-user have been neglected. There is a lack of research on the investigation of the personal preferences of the end-users concerning material evaluation and selection (Zhang *et al.*, 2019). A comprehensive literature review reveals that there is a lack of knowledge on a standard method or proper material selection guidelines developed for tropical climatic conditions.

This study focuses on reviewing the existing knowledge on construction material selection that supports making decisions on materials, and parameters that are involved in material selection frameworks, and identifying possible selection methods. Searching using the keywords on a specific database for a subject is a commonly used procedure for a review (Yi and Chan, 2014; Ruparathna, Hewage, and Sadiq, 2016). Accordingly, this article has been prepared by reviewing high-impact peer-reviewed journals and conference papers published from 1980 to the present while around 95% of the articles referenced were over the past two decades. The first part of the paper introduces the material selection. The second part describes the factors considered in selecting building materials while part three explores sustainable buildings and materials. Part four gives an outline of the life cycle thinking approach and the sustainability concept. Part five provides the various literary works that have dealt with the material selection based on quantifiable measures. Then the sixth part of the paper shows how decisions are made by combining the quantitative as well as the qualitative aspects and the seventh part describes the multi-criteria decision methods that are most popularly used in presenting selection frameworks and the paper ends with a conclusion. The findings of this review will encourage researchers to propose innovative and industry-centric approaches in selecting the most desirable building materials for construction.

2. Factors affecting building material selection

The most desirable materials are selected by carrying out a preliminary comparative study based on multiple criteria. Expert opinions conclude that the parameters for building material selection need to be comprehensive, transparent, and practical (Akadiri, 2011; Sahlol *et al.*, 2021). Strength is one of the major areas that need to be focused on while selecting a material for any element (Kariyawasam and Jayasinghe, 2016). On the other hand, there are other structural parameters as well as performance criteria that are taken into consideration while selecting the most suitable material. Durability and thermal performance are predominant factors when the building performance is considered (Jayasinghe, Jayathilake, and Dissanayake, 2016).

In addition to structural parameters and durability aspects, the factors influencing the material selection could be categorized under different themes. Peuportier et al. (2013) have listed various goals and objectives under economic, ecological, social, and cultural aspects under the concept of eco-design which paves the way for sustainability (Peuportier, Thiers and Guiavarch, 2013). Sahlol et al., (2021) identified various parameters and categorized them under environmental, socioeconomic, and technical categories in selecting sustainable materials (Sahlol *et al.*, 2021). Several literature works have listed various sustainability factors affecting material selections (Seo, Tucker and Ambrose, 2004; Abeysundra *et al.*, 2007; Akadiri, Olomolaiye and Chinyio, 2013a; Peuportier, Thiers and Guiavarch, 2013; Hossaini *et al.*, 2014; Zuo and Zhao, 2014; Lambrechts *et al.*, 2019; Sahlol *et al.*, 2021). Accordingly, saving energy, reducing waste, or proper disposal of waste which includes recycling and reuse, reducing the usage of toxic materials or materials with hazardous content, reducing life cycle costs, health and safety of occupants, improving thermal comfort, and use of local regional materials are the highly repeated parameters. Consideration of several qualitative, as well as quantitative parameters in selecting desirable materials, would lead to sustainable buildings.

3. Sustainable Buildings and materials

Sustainability enables one to meet current requirements without sacrificing the ability of future generations to satisfy their own (Troyer, 1990; Peuportier, Thiers, and Guiavarch, 2013; Hossaini *et al.*, 2014). Sustainability has emerged as a popular concept in recent times as allowing a pathway for a desirable society (Holden, Linnerud, and Banister, 2014). To rectify all the global issues, the concept of "Sustainable development" is highly essential (Dimitrokali, Hartungi, and Howe, 2010; Hossaini *et al.*, 2014). The building industry is in essential need of proposing frameworks to develop a sustainability assessment due to the rapid growth of construction (Hossaini *et al.*, 2014).

Akadiri et al., (2013) have mentioned that the current methods of selection of building materials do not satisfy the major sustainability issues and the authors stated that material framework is an important strategy for proposing sustainable building material selection (Akadiri, Olomolaiye and Chinyio, 2013a). According to Ortiz et al. (2010), for a selection process to be sustainable, it needs to take into account environmental, economic, social, and technical factors (Ortiz, Pasqualino, and Castells, 2010; Akadiri, Olomolaiye and Chinyio, 2013a). A conceptual framework has been put forth by Omer and Noguchi (2020) to comprehend the role that building materials play in achieving the Sustainable Development Goals (SDGs) (Omer and Noguchi, 2020). The use of a multi-criteria method for material selection has been stressed as they indicated that the building materials have a stronger impact on the accomplishment of numerous Sustainable Development Goals (SDGs).

Buildings have more environmental effects, both direct and indirect. Buildings utilize energy, water, and raw materials during various stages like construction, occupancy, refurbishment, repurposing, and demolition. They also produce waste and emit potentially dangerous air emissions. Thus, green building standards, certifications, and rating systems are emerging while aiming at mitigating the impact of buildings on the natural environment through sustainable design. Various countries developed several guidelines and rating systems that can be used to guide and assess construction projects. Some such systems are Leadership in Energy and Environmental Design (LEED), Building Research Establishment Environmental Assessment Method (BREEAM), Green Mark (GM), Building Environment Assessment Method (BEAM), Assessment Standard for Green Building (ASGB), Comprehensive Assessment System for Built Environment Efficiency (CASBEE), German Society for Sustainable Building (DGNB), High-Quality Environmental Standard (HQE), EEWH(GBRT in Taiwan), and Green Star (GS) (Wen *et al.*, 2020). Sahlol et al. (2021) have considered five international, national, and regional rating systems such as Green Pyramids (Egypt), PEARL (United Arab Emirates), LEED (United States), BREEAM (United Kingdom), and Green Globes (Canada) to consider a vast diversity of cases and have tabulated the parameters as in a summarized form (Sahlol *et al.*, 2021). The authors have introduced a group summation indicating the number of rating systems out of the considered ones consisting of each parameter. Accordingly, waste management, recycling of materials, use of local materials, and durability are ranked as important at a higher level while resource reuse use of salvage materials, and use of certified wood fall under the next level. Though the different Green Building rating Systems (GBRS) have been developed in different parts of the world under different contexts, material selection has become a common concern emphasized by all while contributing directly or indirectly to sustainability (Sahlol *et al.*, 2021). The rating systems are usually frameworks with scoring systems.
Wen et al. (2020) have unified ten GBRSs and have presented three levels, namely, categories, subcategories, and criteria where the categories identified are environmental, economic, and social qualities (Wen *et al.*, 2020). Several criteria and indicators were concluded under the mentioned categories. The summary of parameters provided by the authors clearly shows that material usage creates a greater impact on achieving green buildings. The life cycle thinking-based approach is a very useful concept that could be used to compare and select building materials over the long run (Gurupatham, Jayasinghe, and Perera, 2021).

4. Life Cycle thinking-based approach and sustainability

The life cycle thinking approach is a cradle-to-grave approach that considers all stages of a building's life and supports the material selection in a better way. It could be considered when evaluating costs and impacts throughout the life of a building (Lu, Le, and Song, 2017). Several countries with varying climatic conditions utilize the above concept in applications such as cost, performance, consumption of energy, impact on human health, and environmental issues over the long run (Jun *et al.*, 2019; Gurupatham, Jayasinghe, and Perera, 2021). Various concepts could be applied from a life cycle perspective to encourage a better selection of materials (Bruce-Hyrkäs, Pasanen, and Castro, 2018).
Life cycle cost (LCC) is the cost that includes the costs incurred at all stages from the extraction of raw materials for production to the end of life (Li *et al.*, 2020; Gurupatham, Jayasinghe, and Perera, 2021). It could be used to evaluate the economic performance of several investment alternatives over a specified period of commercial interest considering suitable economic factors (Norman, 1990; Kirk and Dell'Isola, 1995; Bull, 2003; Flanagan, Jewell and Norman, 2005; ISO, 2008; Dwaikat and Ali, 2018;

AbouHamad and Abu-Hamd, 2019; Gurupatham, Jayasinghe and Perera, 2021). The International Standard ISO 15686-5:2008 could be used to conduct LCC (Dwaikat and Ali, 2018; Gurupatham, Jayasinghe, and Perera, 2021).

Life Cycle Assessment is a technique for an integrative approach to the environmental assessment that is applied to evaluate the environmental performance of products and processes in most cases (Lu, Le, and Song, 2017)(Perera *et al.*, 2017; Gurupatham, Jayasinghe and Perera, 2021). LCA is carried out by following ISO standards such as 14040 and 14044 (Ferrández-García, Ibáñez-Forés and Bovea, 2016; AbouHamad and Abu-Hamd, 2019; Gurupatham, Jayasinghe and Perera, 2021). Buildings for Environmental and Economic Sustainability (BEES), Life Cycle (LC) Aid, Athena Eco-Calculator, SimaPro, and Athena Impact Estimator are some of the commonly used programs for LCA computations (Ferrández-García, Ibáñez-Forés and Bovea, 2016; Lu, Le and Song, 2017; Gurupatham, Jayasinghe and Perera, 2021).

Energy is one of the key aspects when it comes to sustainability. Buildings consume a considerable amount of energy at every stage of their lifetime and the building materials are responsible for a greater share of the energy consumed (Yüksek, 2015). Energy consumption takes place in the form of embodied as well as operational stages and leads to emissions as embodied and operational emissions (Thevarajah *et al.*, 2020; Gurupatham, Jayasinghe, and Perera, 2021). Emissions create a significant impact on ecology. Further, energy saving is very important in economic growth and social development (Yüksek, 2015). Hossaini et al. (2014) have concluded that the environmental performance of a building is highly dependent on service life energy (Hossaini *et al.*, 2014). The choice of building materials contributes highly to thermal performance and thus contributes to energy consumption.

The concept of eco-efficiency combines the environmental as well as the financial impacts of products or systems over the entire life span (Perera *et al.*, 2017). Lower costs with lower environmental impacts lead to a higher value of Eco-efficiency (Ferrández-García, Ibáñez-Forés, and Bovea, 2016). Cost-effective and environmentally friendly alternatives are found when compared and ranked using eco-efficiency (Ferrández-García, Ibáñez-Forés and Bovea, 2016; Perera *et al.*, 2017, 2018; Gurupatham, Jayasinghe and Perera, 2021).

In addition to economic and environmental aspects, the inclusion of social aspects leads to life cycle sustainability (Wen *et al.*, 2020). Recent studies have carried out S-LCA (Social Life Cycle Assessment) as a measure of social impact (Yıldız-Geyhan, Altun-Çiftçioğlu and Kadırgan, 2017). S-LCA is a social impact assessment method that accesses the social aspect of a project throughout its lifetime (Benoît-Norris *et al.*, 2011). The impact categories such as health and safety, security, working conditions, human rights, and socio-economic repercussions could be considered examples of social aspects (Yıldız-Geyhan, Altun-Çiftçioğlu and Kadırgan, 2017).

There are several tools available to improve material selection sustainably. Eco-design is such a tool. It is a concept that incorporates all the above aspects and leads to the achievement of Green Building certifications and environmental product declarations (Bruce-Hyrkäs, Pasanen, and Castro, 2018). Several studies that focused on life cycle thinking have examined the eco-design concept (Malcolm, 2011; Dalhammar, 2015; Bundgaard, Mosgaard, and Remmen, 2017). According to ISO 14006, eco-design is the incorporation of environmental considerations into product design and development to minimize harmful environmental impacts throughout a product's life cycle (ISO, 2011; Lambrechts *et al.*, 2019). It is a very useful tool that sets minimum requirements for the performance of products (Hinchliffe and Akkerman, 2017). Although a very useful concept, the industry has been slow to adapt to eco-design principles (Dekoninck *et al.*, 2016; Lambrechts *et al.*, 2019).

Rossi et al. (2016) combined the tools and methods frameworks after a thorough literature review which shows a growing interest in the implementation of eco-design (Rossi, Germani, and Zamagni, 2016).

The identified tools and methods are the keys to practicing eco-design that includes economic, ecological, social, and cultural parameters and thus contributes to sustainable development (Negny *et al.*, 2012; Peuportier, Thiers and Guiavarch, 2013; Rossi, Germani and Zamagni, 2016; Cicconi, 2020). Lambrechts et al. and Zuo & Zhao describe the Key dimensions of Eco-Design as environmental/technological aspects, social aspects, and economic aspects (Lambrechts *et al.*, 2019)(Zuo and Zhao, 2014). Recent literature has listed the goals and objectives of the eco-design concept (Peuportier, Thiers, and Guiavarch, 2013; Zuo and Zhao, 2014; Lambrechts *et al.*, 2019). Technological, managerial, and behavioral success factors collectively contribute to eco-design applications (Lambrechts *et al.*, 2019). Energy saving is an important factor of eco-design that addresses many factors related to sustainability as it creates an impact in almost all sectors that could be considered under sustainable development (Peuportier, Thiers, and Guiavarch, 2013). Hence, eco-design is a concept that includes the triple bottom line aspects of sustainability could be identified as a suitable tool for selecting sustainable building materials.

5. Material selections with the aid of quantifiable methods

It becomes easy to compare materials based on quantifiable approaches. Experimental testing procedures, calculations, and quantification with the help of computer simulations are approaches to compare and select materials. The quantifiable testing procedures are further elaborated under sections 5.1 and 5.2.

5.1. Experimental testing procedures

All over the world, a greater number of tests are associated with the construction industry and they are carried out to test the elements and building materials (Hoła and Schabowicz, 2010; Schabowicz, 2015, 2021; Szewczak, Winkler-Skalna and Czarnecki, 2020). Experimental testing procedures are a subset of sustainable material section methods (Szewczak, Winkler-Skalna, and Czarnecki, 2020). The materials are tested for specific applications. Flaws and defects are identified as a result of experimental tests (Schabowicz, 2021). The tests could be either non-destructive semi-destructive or destructive (Schabowicz, 2021).

Strength and durability concerns could be easily quantified by performing experimental procedures. Kariyawasam & Jayasinghe (2016) have carried out the strength as well as durability testing of cement-stabilized rammed earth walling material that has enough strength and durability while having a lower embodied energy with the variation of soil material such as sandy laterite, gravelly laterite, and clayey laterite and has found that the sandy laterite is the best soil type out of the considered soil types (Kariyawasam and Jayasinghe, 2016). To select the proper soil types, quantifiable testing procedures have been followed. C. Jayasinghe et al. (2016) have tested the load-bearing properties such as compressive strength, flexural strength perpendicular to bed joints, and flexural strength parallel to bed joints for the composite masonry constructed with recycled building demolition waste and cement stabilized rammed earth using quantifiable testing procedures (Jayasinghe, Fonseka and Abeygunawardhene, 2016). Similarly, numerous examples could be found in the past literature on performing experimental testing procedures to select suitable building materials. Hence, the results of testing could be an easy method of ranking materials.

5.2. Calculations and computer simulations

Certain parameters like costs and impacts could be quantified by calculations. Also, previous experimental results, databases, and literature could be used to derive available data on various aspects and thus calculations based on them can lead to quantification. Computer simulations have also been identified as a quantification technique for factors like thermal performance and energy consumption. Selective literature examples on quantifications using calculations or computer simulations have been discussed in this section.

AbouHamad & Abu-Hamd, 2019 have carried out a framework selection system in which reinforced concrete framing (RC), structural steel framing (SS), and cold-formed steel framing (CFS) were compared (AbouHamad and Abu-Hamd, 2019). The framework has been carried out with the aid of Life cycle cost and sustainability. The framework incorporates building information modeling and energy simulation in order the compare the alternatives in the case of LCA and LEED points that have been used to access sustainability. In addition to that Monte Carlo simulation has been used to account for uncertainties and with the help of sensitivity analysis, the factors creating higher impact have been identified.

Hossaini et al. (2014) have performed a case study on Life Cycle Sustainability by Analytical Hierarchy Process (AHP) to propose a sustainability evaluation framework by including several environmental as well as socio-economic factors (Hossaini *et al.*, 2014). For this purpose, two typical six-story concrete and wood-framed houses were selected. To evaluate the triple bottom line (TBL) sustainability performance indicators of buildings, which are also known as sustainability performance indicators of sustainability, a cradle-to-grave method was used. The impacts were aggregated using AHP into a unified sustainability index and were compared.

Halwatura & Jayasinghe (2009) have carried out a comparison of roofing and insulations with the aid of life cycle costs including initial and running costs and have compared the Net Present Value (NPV) (Halwatura and Jayasinghe, 2009). The authors utilized computer simulation with DEROB - LTH (Dynamic Energy Response Of Building) and cost analyses for the above material comparisons. Udawattha & Halwatura (2018) used real-world analysis, simulation analysis, and validation to examine the thermal performance of walling materials such as Burnt Bricks (BB), Hollow Cement Blocks (HCB), and Mud Concrete Blocks (MCB) (Udawattha and Halwatura, 2018). A case study approach was used on actual buildings with the same plan form but three different walling materials. The authors have also compared walling materials such as Brick, Hollow Cement blocks, Cabook, and Mud concrete blocks with the aid of Life Cycle costs(Udawattha and Halwatura, 2017). They have used an energy accounting hierarchical structure to find the life cycle costs. They ranked the materials individually based on parameters such as Initial cost, Life cycle cost, operational energy costs, embedded energy, environmental suitability, and carbon footprint and also finally provided an overall ranking of the considered materials. Ferrández-García et al. (2016) have analyzed the eco-efficiency of interior partition walls from a life cycle perspective (Ferrández-García, Ibáñez-Forés and Bovea, 2016). The LCA methodology had been applied and suitable alternatives were chosen such that they fall under lower cost and lower environmental impact. The graphical method of Interpretation of environmental indicators against cost has been used as a way to identify the alternative with lower cost as well as lower environmental impact.

Perera et al. (2017) have carried out a case study on the eco-efficiency analysis of recycled material for residential construction (Perera *et al.*, 2017). The authors have compared three different alternatives for walling such as conventional wall system, conventional with Inculcated Concrete Foam (ICF) and Recycled Concrete Aggregate (RCA) concrete walls, and ICF and RCA concrete wall system. They calculated LCC and LCA scores and thus calculated the eco-efficiency to compare the alternatives and select the best alternative. Gurupatham et al. (2021) have followed a similar methodology to compare the performance of the Compressed Stabilized Earth Block (CSEB) walling over conventional materials like Burnt Clay Bricks (BCB) and Cement Sand Blocks (CSB) over the long term (Gurupatham, Jayasinghe and Perera, 2021).

Based on an examination of embodied energy and carbon footprint, Dissanayake et al. (2017) and Thevarajah et al. (2020) compared EPS wall panels to more traditional building materials including cement sand blocks and burned clay bricks (Dissanayake, Jayasinghe, and Jayasinghe, 2017; Thevarajah *et al.*, 2020). The above research works have been carried out with the aid of a case study approach. The authors quantified the energy as well as the emissions and ranked the materials individually based on Embodied energy as well as equivalent carbon emissions due to embodied energy.

Thus, in light of the aforementioned literature findings, it is possible to conclude that several researchers have used energy simulations and calculations to compare building materials. In case of encountering situations of combining two different parameters, methods such as quantifying to a common index, graphical representation, and overall rankings have been used. Moreover, the case study approach has been identified in most of the studies as an effective strategy to compare several alternatives.

6. Combination of qualitative and quantitative methods for building material selection

Quantitative as well as qualitative factors together contribute to selecting suitable materials in most cases. In addition to the quantifiable factors to compare personal preferences, survey-based approaches are used. The majority of the time, survey-based methods are used to compare social concerns including thermal comfort, good interior (aesthetics), ability to construct quickly, and durability (Abeysundra *et al.*, 2007). Interviews, surveys, and on-site observation are some of the best techniques identified in the literature to determine user requirements. Some pieces of literature have emphasized building performances by integrating the User-Centered Design (UCD) approach into the building sector (Bullinger *et al.*, 2010; Kurnianingsih *et al.*, 2014; Zhang *et al.*, 2019). Investigating the end-users throughout the early stages of a building's construction could increase product quality and performance (Zhang *et al.*, 2019). Selective examples of material selection with the combination of quantitative as well as qualitative factors have been discussed in this section.

Emmanuel (2004) has compared walling materials (Emmanuel, 2004). The author assessed the environmental suitability of alternative walling materials and quantified the three parameters such as embodied energy, life-cycle costs, and re-usability into one parameter as the “Environmental Suitability Index” and the materials were ranked based on the above index. In addition to the quantifiable parameters survey-based approach has also been followed.

Mesa et al. (2020) have developed a material durability indicator or MDI to compare and select alternative building materials by ranking the MDI value obtained (Mesa, González-Quiroga, and Maury, 2020). The proposed MDI provides a balance between the durability and environmental impacts in selecting suitable materials from available alternatives. It incorporates chemical durability, mechanical durability, and environmental performance which have been calculated in separate formulas. The environmental performance has been computed based on energy consumption whereas the other factors were calculated using appropriate constant values for each material based on liked scale values. Hence, it could be observed that when combining several quantitative and qualitative criteria, individual assessment of each criterion or reduction to a suitable index has been followed in the past literature. In addition to that, Multi-Criteria Decision Making (MCDM) techniques have been used to combine several criteria and form a decision support system that would affect suitable selections. Selective examples of the use of MCDM have been described.

Abeysundra et al. (2007) have carried out Environmental, economic, and social analysis of materials for doors and windows in Sri Lanka from in life cycle perspective (Abeysundra *et al.*, 2007). The authors have compared timber and Aluminium. The materials were compared individually with the aid of environmental, economic, and social scores. A survey-based approach was followed to compare the social parameters. The authors suggested the Analytical Network Process (ANP) be a better technique to combine the aspects and select the best material.

Yang & Ogunkah (2013) have carried out A Multi-Criteria Decision Support System for the Selection of low-cost green building materials and components with the aid of AHP by including general or site factors, economic factors, environmental factors, sociocultural factors, technical factors, and sensorial factors (Yang and Ogunkah, 2013).

Knowledge-based Decision Support System for Roofing Material Selection and Cost Estimating (KDSMS) is a framework for choosing roofing materials that was developed by Rahman et al. (2012)

(Rahman *et al.*, 2012). The selection process mentioned above is effective for both qualitative and quantitative knowledge that was gathered from subject matter experts and other technical literature. Materials selection and optimization issues have been resolved using the TOPSIS (Technique of ranking Preferences by Similarity to the Ideal Solution) multiple-criterion decision-making technique. In the work on formwork selection, Krawczyska-Piechna (2017) employed MCDM techniques, with a structured survey distributed to contractors serving as the source of the deciding factors (Krawczyńska-Piechna, 2017). For that, the factors influencing the formwork selection have been obtained through past research works, and to unify the selection method, an expert survey has been used with the aid of a structured survey. The decisive criteria mentioned above were ordered using the Rank Exponent method (Krawczyńska-Piechna, 2017).

Zha (2005) has proposed a web-based advisory system for process and material selection and has used a fuzzy knowledge-based decision support method for multi-criteria decision-making to select material combinations (Zha, 2005). The selection of internal finishes plays a major role as the finishing materials have a greater impact on the sustainability aspects such as environmental, economic, and social (Castro-Lacouture *et al.*, 2009; Zhang *et al.*, 2019). Zhang et al., (2019) have worked on material selection interior finishing (Zhang *et al.*, 2019). The authors have discovered that there are qualitative needs, such as a preference for aesthetics, in addition to quantitative indications like material energy performance and life expectancy. To choose the best finishing materials, they have taken into account both quantitative and qualitative factors and developed an immersive virtual reality (IVR)-based strategy. The suggested IVR takes into account both traditional material performance and aesthetics. To this end, multi-criteria decision-making (MCDM) analysis and material collocation optimization based on interactive particle swarm optimization (IPSO) have been used.

Hence, based on the aforementioned literature findings it could be observed that MCDM has been widely used considering both the quantitative as well as qualitative factors. It could also be noted that the MCDM could be used to incorporate a wide range of factors for material ranking.

Most literature evidence involving MCDM techniques to combine a wide range of factors includes the identification of related performance criteria through expert interviews or industry questionnaire surveys and finalizing the factors by quantification of the level of importance of the considered parameters into an index such as Relative index, Importance Index or Severity Index (Akadiri, Olomolaiye and Chinyio, 2013b; Kamali and Hewage, 2016; Amer and Attia, 2019; Sahlol *et al.*, 2021). Furthermore, the impact of each identified parameter is concluded by MCDM techniques by reducing the survey responses (Akadiri, Olomolaiye, and Chinyio, 2013b; Sahlol *et al.*, 2021). Accordingly, aggregation of the impacts of all parameters results in the comparison and ranking of building materials.

7. Multi-Criteria Decision Making (MCDM)

For the past five decades, Multi-Criteria Decision Making (MCDM) has been identified as a suitable and efficient way to solve complicated problems with multi-criteria and several alternatives (Ho, Xu and Dey, 2010; Abdel-basset *et al.*, 2019). MCDM methods have been recognized since the early 1970s by researchers (Abdel-basset *et al.*, 2019). Several MCDM methodologies can be used to combine several inconsistent criteria. Some of the popularly used methods mentioned in the literature are the Multi-Objective Optimization based on Ratio Analysis (MOORA) (Brauers and Zavadskas, 2006, 2010), the Analytic Hierarchy Process (AHP) (Saaty, 2008), the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) (Abdel-basset *et al.*, 2019). Many of the Multi-Criteria Decision Making (MCDM) is extended to group decision-making (Abdel-basset *et al.*, 2019).

The MOORA method refers to the response matrix of alternatives to the target, applying ratios (Brauers and Zavadskas, 2006, 2010). In this method, each response of an alternative is compared to a target with a denominator that represents all the alternatives related to that objective (Brauers and Zavadskas, 2010). AHP is being widely used in multi-criteria decision-making problems (Saaty, 1980; Zavadskas, Turskis, and Tamosaitiene, 2011; Akadiri, Olomolaiye, and Chinyio, 2013a). To approach sustainable selections, many researchers have used the APH method. (Nassar, Thabet, and Beliveau, 2003; Shapira, Asce, and Goldenberg, 2006; Ugwu *et al.*, 2006; Wong and Li, 2008; Reza, Sadiq, and Hewage, 2011; Wang *et al.*, 2012; Akadiri, Olomolaiye and Chinyio, 2013a). There are four main steps involved in the structuring of a decision into AHP (Zahedi, 1986; Saaty, 2008; Akadiri, Olomolaiye, and Chinyio, 2013a). They are the definition of the material selection problem, identification of objectives, and recognition criteria and attributes. Accordingly, objectives, criteria, attributes, and the selected alternatives are considered from the first level to the fourth. Several studies have been conducted using the AHP method from which further details on AHP could be obtained (Saaty, 1987; Shapira, Asce, and Goldenberg, 2006; Saaty and Shang, 2011; Yang and Ogunkah, 2013). The above method is easy to be applied. However, AHP does not address the uncertainty and ambiguity that arise while determining the relative importance of various traits, which is considered to be a limitation of the method (Medineckiene, Zavadskas and Turskis, 2011; Akadiri, Olomolaiye and Chinyio, 2013a). Also, the discrete scale may not be accurate for interpreting human interpretations (Jaskowski, Biruk, and Bucon, 2010; Akadiri, Olomolaiye, and Chinyio, 2013a).

TOPSIS is a useful and popular approach that could be applied by decision-makers to rectify issues such as vagueness, incomplete data, and uncertainty (Nadaban, Dzitac, and Dzitac, 2016; Abdel-basset *et al.*, 2019). The concept is such that the solution is nearest to the Positive Ideal Solution (PIS) and furthest to the Negative Ideal Solution (NIS) (Nadaban, Dzitac, and Dzitac, 2016). The combination of AHP and TOPSIS, where the determination of weights for parameters is carried out using AHP and ranking with the aid of TOPSIS has also been found popularly in the literature.

Linguistic variables and fuzzy numbers can be used to address the aforementioned issue found in AHP and TOPSIS (Medineckiene, Zavadskas, and Turskis, 2011; Joshi and Kumar, 2016). Many MCDM approaches employ the fuzzy set or intuitionist fuzzy set theories (Abdel-basset *et al.*, 2019). For upcoming investigations, Hossaini et al. (2014) advise uncertainty analysis using probabilistic and fuzzy-based methodologies (Hossaini *et al.*, 2014). Fuzzy is commonly used in Group decision-making (Li and Yang, 2004; Ölçer and Odabaşi, 2005). To find out the final priority weights based on fuzzy numbers; the Synthetic extent analysis method is applied. The application of Fuzzy numbers into AHP leads to fuzzy extended AHP (FEAHP) (Chan and Kumar, 2007; Akadiri, Olomolaiye and Chinyio, 2013a). Fuzzy TOPSIS is one of the best methods to select the best material out of several options (Nadaban, Dzitac, and Dzitac, 2016) that could automate the process and overcome ambiguity and uncertainty (Kore, Ravi and Patil, 2017).

8. Conclusion

The selection of building materials is becoming critical with several alternatives emerging recently. Quantifiable factor-based rankings are easily carried out using experimental testing procedures, calculations, software, and energy simulations. Qualitative factors are determined based on human judgments whereas questionnaire surveys and interviews are popularly used. Several parameters could be identified as factors affecting sustainable development in the selection of building materials. When combining several factors that influence the material selection, Multi-Criteria Decision (MCDM) is popularly followed. AHP has been identified as a popular tool to find the weightage of factors affecting material selection as well as it is used to the extent of selecting from several alternatives. Also, TOPSIS has been used in comparing alternatives. To rectify the drawbacks fuzzy numbers are recommended which could lead to better decision-making when selecting building materials.

Since both quantitative and qualitative parameters are involved in sustainable material selection, multi-criteria decision-making could be recommended as a suitable measure that combines various parameters.

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ANALYSIS OF MIDDLE-INCOME HOUSING MARKET IN COLOMBO MUNICIPAL COUNCIL AREA: SOCIO-PSYCHOLOGICAL FACTORS FROM STATE SECTOR PROFESSIONALS' POINT OF VIEWS

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Abstract: State sector professionals representing 32.6% of the total state sector employees represent the well-educated and rational middle-income households working in the city of Colombo. The market trends in the housing industry show residential developments being targeted toward these working professionals who commute to the city daily. However, the literature review revealed that qualitative data such as motivational, attitudes and social status needs reflecting their socio-psychological characteristics which affect housing satisfaction are not available adequately. More importantly, satisfaction of these would improve the quality of housing which is a major factor in developing sustainable cities & communities. Identifying the gap and the importance of such qualitative data about the consumer group, the study focused on analyzing the socio-psychological factors determining the middle-income housing demand of the state sector professionals working in the CMC area. Considering the nature of the data, a mixed-method approach was followed using two basic methods. The data collected from in-depth interviews were analyzed using content analysis to identify the socio-psychological characteristics. The qualitative data collected using a semi-structured questionnaire survey with a sample of 210 respondents were analyzed using Ordinal Logistic Regression analysis studying the influences of socio-psychological characteristics on their housing preferences. Contrary to the characteristics of the consumer, the results revealed that the study population is more focused on safety, security, freedom, and privacy than esteem needs, as their major motivations in choosing their dwelling and such aspects have a larger influence on their housing preferences. The social status & esteem needs were communicated to a lesser extent and the influences of such needs on the housing preferences were shown to be very low. Further, the analysis explained that this outcome may reflect the consumer's emotional reactions to the current economic situation in the country.

Keywords: Middle-income housing; Motivation; Attitudes; Social status; Housing preferences; State-sector professionals

1. Introduction

Colombo is the commercial capital of the country, which has a service-oriented economy, 72.7% of the employed population represents the service sector (Department of Census and Statistics, 2019). Further, 32.6% of the government sector which is a higher representation than in the private sector are the professionals who represent the middle-income households working in the city (Department of Labour, 2020), (Department of Labour, 2022). With the growth of the service sector, middle-income professionals are considered a major attraction for the housing market and housing developments are targeting this category in and around the city (Niriella N. C., 2017), (Ministry of Housing and Construction, 2016), (Colombo Municipal Council, 2019). As per Arunathilake (2013), middle-income consumers are rational, fostered in affordable & quality products, and are selective buyers with different socio-economic and psychological natures than the rest. However, the literature revealed that qualitative data such as socio-psychological data existing on this consumer category is far from satisfactory where the available data are only quantitative in nature such as the income level, family size, floor area, costs, and profits. The qualitative nature of the consumers expressing their socio-cultural needs, and internal influences such as socio-psychological requirements are not explored adequately (Niriella N. C., 2017), (Niriella N. C., Housing for Metropolitan Poor and Rich in Sri Lanka: Emerging Features., 2016), (Niriella N. C., Social Mobility and Class Formation: An Analysis of the Housing Market in Colombo, Sri Lanka, 2012), (Nawaratne, 1997).

Sustainable Development Goals by UNDP states that ensuring access for all to adequate, safe, and affordable housing is a target, and the socio-psychological needs of the users are equally important concerns in achieving adequate housing to live in peace, security, and dignity (United Nations Development Programme, 2023), (United Nations , 2023), (United Nations, 2009). Therefore, social and psychological requirements are vital to achieve housing satisfaction and quality in housing. Further, considering the user perspective, housing is a multi-attribute product and the choice of it is a complex decision. The internal determinants such as motivations, attitudes, social status/positions &, etc. are vital in providing suitable housing for the user (Kanagal, 2016), (Ramya & Ali, 2016), (Jisana, 2014), (Zavei & Jusan, 2010). Other than the affordability and availability, consumers demand different types and quality of housing suitable to their characteristics and expectations and such requirements largely depend on the social, psychological, behavioral, and institutional perspectives (Oktay, Karaaslan, Alkan, & Celik, 2014), (Ali, Rahman, & Ghani, 2018). Considering the nature of this consumer group, the suitability and the quality of the products are major concerns for the consumer purchase decision (Arunathilake, 2013). Likewise, the lack of such data about the consumer & their housing needs may question the quality and suitability of the existing housing supply resulting in unsatisfactory housing as well as unsustainable growth of the city. Therefore, the lack of adequate comprehension of such data is a major knowledge gap in the current market. Taking into account the current knowledge gap identified in the market, this study focuses on analyzing the socio-psychological factors; motivations, attitudes, and social status needs determining the middle-income housing demand for the state sector professionals working in the CMC area.

2. Methods

Considering 11.8% of representation in divisional secretariat divisions in the country, the state sector professionals who work in the CMC area were identified as the study population. The sample criteria including economic and employment status were identified through the existing literature on middle-income households.

The study was conducted adopting a mixed method where in-depth interviews and a questionnaire survey were carried out to collect primary data. To identify the characteristics reflecting the social & psychological needs in housing, motivation, attitude & social status needs of the respondents were inquired. Initially, in-depth interviews were conducted on socio-psychological characters using a convenient sample of 09 respondents. The textual data collected from the in-depth interviews were analyzed using conceptual content analysis. These data were coded, categorized, and then interpreted using an interview guide to identify the perceived socio-psychological characteristics. Further inferences were made using published theories as an analytical generalization. Secondly, a questionnaire survey was carried out to gather data about the demographics, housing preferences, and socio-psychological needs. The operationalization of the variables (latent) was utilized for defining, measuring & manipulating data about the variables in improving the quality of results. Considering the limitations in accessibility and population size, a sample of 210 respondents was identified using multi-stage cluster sampling techniques. The nominal and ordinal categorical data were analyzed using descriptive as well as inferential analysis, and Spearman Correlation analysis. Ordinal categorical data were analyzed using descriptive and inferential analysis and ordinal logistic regressions.

3. Results & Discussion

3.1 Demographical background

The demographic characteristics of the study population were represented by gender, age categories, lifecycle stages, education levels, employment roles, industry & professions, and income categories. The following graphics explain a brief representation of the study sample. The representative sample was done ensuring the representation of varied professions, employment roles, industries, age and life cycle stages, income levels & gender.

Gender	Percentages
Female	64.29%
Male	35.71%
Total	**100.00%**

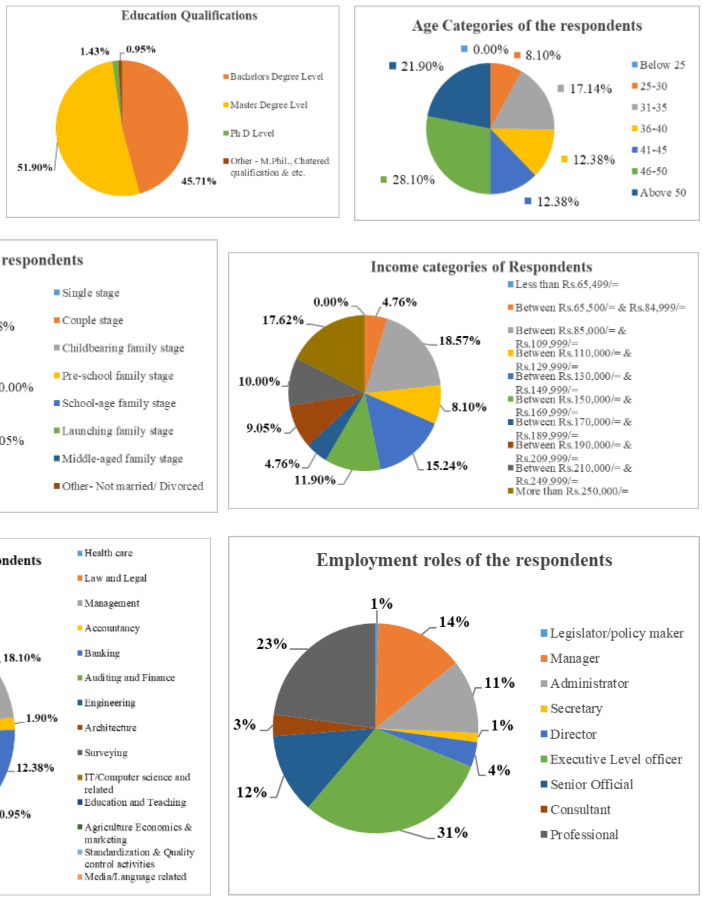

Figure 1: Brief representation of demographic data of the study sample.

3.2 Socio-psychological needs of housing

Considering the in-depth interview data, it was identified that the respondents have expressed their motivation for housing as not only safety and security but also social and self-esteem motivation. It is depicted percentage-wise in Figure 2. The results showed more appearances on safety/security, social & self-esteem needs. However, the self-actualization needs were expressed as a lesser priority when discussing their motivations in choosing housing.

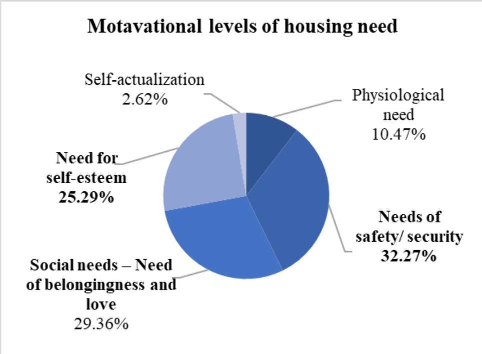

Figure 2: The frequency of appearances of perceived level of motivations.

Self-motivation such as the sense of security, the privacy of the family & freedom were major motivations behind choosing housing. Considering the level of motivations, it shows that their major motivation is the safety and security needs followed by social needs & esteem needs. The results showed that their motivation for housing as a pleasurable product expressed the importance of esteem needs in choosing their house, hence according to the ERG theory by Clayton P. Alderfer (Estaji, 2014), housing is not just an existence need, but also a growth need explaining their motivations in self-esteem, social relationships, etc.

Similarly, as shown in Figure 3, it was expressed that their priority is the high utility and functionality of the house. Further considering the frequencies of appearances, it showed their positive attitude towards the ability to stand their family values as well as the ability to express their social esteems and roles.

The results on motivational needs revealed that the respondents have shown a positive attitude towards the utility and functionality of housing followed by the ability to express and support their values, and esteem needs of family as equally important concerns.

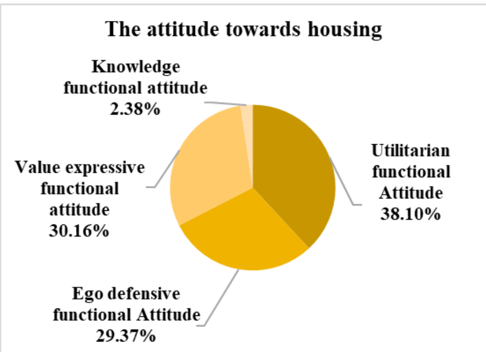

Figure 3 - The frequency of appearances of perceived attitude towards housing.

Considering the social status needs in housing, the ownership, the materials used in the house & the type of housing were represented as a priority in expressing their esteems when choosing housing. The ownership was majorly discussed as the most important purchase providing social, economic, and psychological securities in their life. One major finding was that as discussed in the studies done by Shi & others (Shi, 2000), (Beyer & Montgomery, 1955) , the respondents were reluctant to express their needs in esteem and social prestige needs and such needs were expressed indirectly.

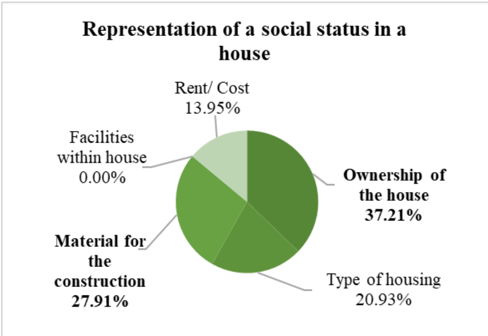

Figure 4 : The frequency of appearances of perceived social status needs in house.

Accordingly, as per the existence, relatedness, and growth (ERG) theory (Estaji, 2014), it can be argued that housing is more than just a functioning house with security and safety, is rather one with more abstract values such as esteems and appearances explaining the theory of symbolic interaction (Smith & Bugni, 2006) expresses their needs in communicating shared meanings, thoughts, actions &, etc.

However, the outcome of the questionnaire survey which was carried out at a later stage of the data collection period, resulted in a contradictory outcome than the above, indicating that there is a noticeable change in the socio-psychological needs of a house. Considering the motivations, they have given priority to safety & security, and physiological needs, and the rest have been given a significantly lower priority. Regarding the attitude, the only utility function was given a higher priority and the rest were given a very low level of importance. Similarly, only housing ownership was given a higher priority. The other aspects such as materials, appearances, and type of housing in representing the social status or their roles were given less significance. Therefore, the results of the questionnaire survey revealed that they have given a significantly lower priority to abstract values such as esteem needs, value expressive qualities, and other needs that represent their esteem and values in housing. Rather they have given a significantly higher priority and significance to the basic and functional values than the abstract values of a house.

The analytical generalization done through existing literature explains that changes in consumer behaviors can occur during economic and recession periods in a market. Therefore, the analysis of results with the existing literature explains that such outcomes may explain the emotional reactions to the current economic situation in the country. The change in the motivations, attitudes and social status needs from abstract needs to basic and viable needs can be a reflection of emotional reactions due to the uncertainty of the economy becoming stricter and deficient to their limited disposable income levels (Quelch & Jocz, 2009), (Sharma & Sonwalkar, 2013).

Further, the research done on the recession psychology model by Harvard Business Reviews presented below shows this consumer group can be explained under the segment of “Pained-but-Patient”. As per the segmentation, it shows that such consumer seeks their essential products with their favorite brands, but they settle for cheaper and less preferred alternatives. They cut back the frequency and quantity of non-essential goods or treats. They delay major purchases and repair rather than replace such purchases. Postponable purchases will be delayed, and expendables will be deeply curtailed.

Therefore, the findings about the socio-psychological characteristics of this consumer revealed that during this period, they were more focused on the basic and functional needs of housing rather than the abstract values expected in a normal situation. It is due to the fact they are resilient but less confident, they economize and are less aggressive when making purchases.

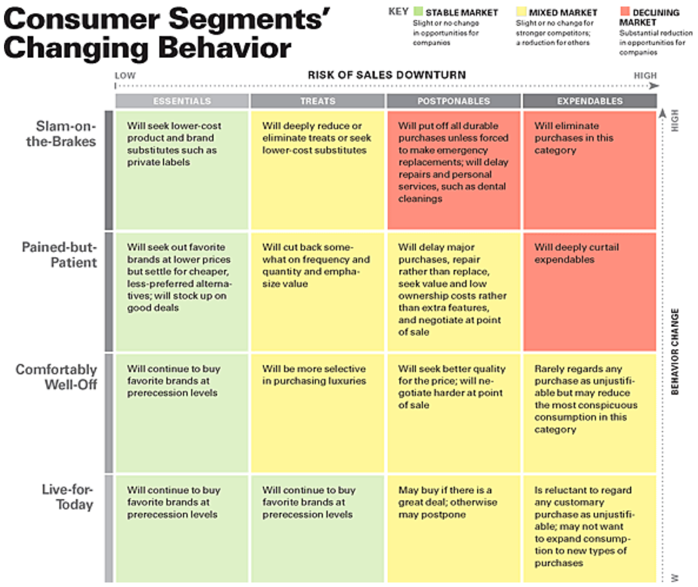

Figure 5: Customer Segments' Changing Behaviors *(Quelch & Jocz, 2009)*.

3.2 Housing preferences

The analysis of the questionnaire survey revealed that the ownership of the house is the most important attribute when selecting housing. The level of privacy provided in the house is ranked as the second most important attribute followed by the safety in the neighborhood, conformable access & personal freedom as the most important attributes among all 37 attributes.

The sense of connectedness in the neighborhood, proximity to a recreational area, level of acceptance in the neighborhood, sense of belonging to the neighborhood and proximity to relatives/ friends were ranked as the least important attributes in selecting their house. Nevertheless, it shows that the social environment of the neighborhood is given lesser importance when choosing houses.

Housing Attributes	Mean	Std. Deviation	Order
Ownership of the house - DT	8.5886	1.09276	1
Level of privacy – DQ-in	8.3710	1.33153	2
Level of safety and security in the neighborhood – SE	8.2371	1.54150	3
Comfortable access - DN	8.1952	1.28851	4
Personal Freedom and values - HV	8.0057	1.13722	5

Figure 6 : Housing preferences - five most important housing attributes.

Sense of connectedness with the neighbors – SE	6.5743	1.58289	33
Proximity to public parks/ recreational areas - DL	6.3524	2.22419	34
Level of acceptance by the neighbors – SE	6.2400	1.75317	35
Sense of belonging to the neighborhood - SE	6.0171	1.87721	36
Proximity to relative's/ friend's houses - DL	5.7143	2.62383	37

Figure 7: Housing preferences - five least important housing attributes.

Therefore, the results revealed that personal safety, security & freedom are more important to this consumer group and they give a comparatively low level of significance to the social environment when selecting a house.

Further, the following chart presents the preferred general house status/ profile demanded by the study population expressing the general requirements for housing demand in the CMC area.
Hence, this explains that irrespective of the locations of their working places & children's schools, the majority of them prefer to have detached housing located out of the city rather than condominiums located in the city.

Attribute	Preference
Type Of Tenureship	Freehold ownership
Type of House	Detached housing
No. of bedrooms preferred	03-04 bedrooms
Preference on condominiums	Not preferred
Preferred locations	Out of Colombo Dist.

Figure 8: Preferences on General House Status.

3.3 Influence of socio-psychological characteristics over housing preferences.
The set hypotheses were tested using an ordinal logistic regression model testing the association (independent influences) between the dependent and independent variables.

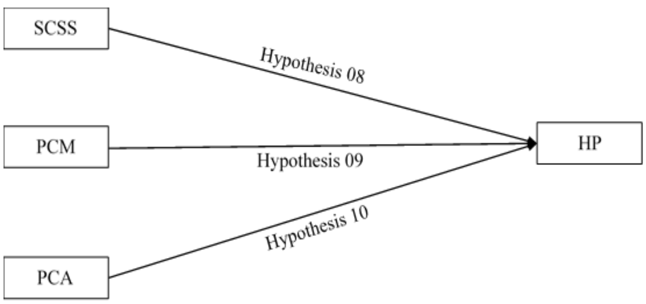

Figure 8: Hypothesizes to test the associations between ID and DV.

The output of the analysis resulted in P-values less than 0.05 for hypotheses 09 & 10, explaining that the motivation and the attitudes of the users towards housing are associated with housing preferences. In contrast, hypothesis 08 was not significant and it does not show a significant association with the social status needs and housing preferences. Exp(B) values: odds ratio indicated the odds of being in a higher level of housing preference increases by a factor of 2.402 for every one-unit increase in motivation and by a factor of 1.732 for every one-unit increase in attitude. Further, the Pseudo R-Square value was 0.332 (Nagelkerke) explaining that 33.2% of the variation in housing preferences level is explained by the socio-psychological characteristics of the user.

Considering the influences of the socio-psychological characteristics of the user on the housing preferences, the results revealed that the user motivations and attitudes towards housing influence the housing preferences. Hence it can be argued that understanding consumer motivation and attitude may help in increasing housing satisfaction. However, unlike these two aspects, social status needs do not significantly influence the housing preferences of the study group. Nevertheless, as explained above, this outcome may explain the reflection of the emotional reaction toward current economic conditions in the country.

3. Conclusion

Socio-psychological needs are internal factors that influence the consumer's behaviors, choices, and preferences. Housing is a multi-attribute product where the preferences on it is a complex decision which determines the housing demand in a market. Hence the understanding of the socio-psychological characteristics and its influences on housing preferences can directly improve the quality of housing supply targeting user satisfaction as well as the sustainability of the city and its growth. However, to the best of my knowledge, the research on this subject area is lacking and unsatisfactory, and the lack of adequate knowledge on such data is a major knowledge gap in the market questioning the housing supply quality in the current context. In this study, the socio-psychological factors are analyzed under three major aspects which are motivation, attitude, and social status & then such characteristics were analyzed to identify the influence of housing preferences of the study population.

Explaining the current market demand for housing, the study revealed that the study population gives priority and significance to the basic and viable uses of the house where functionality, safety & security are prioritized when selecting housing. The esteem needs, social needs, the ability to support values, status &, etc. are considered less important. This outcome reflects the theory of the recession psychology model by Harvard Business Reviews explaining the changes in consumer behavior changes (Quelch & Jocz, 2009). During this uncertain period, they seek essential needs such as housing ownership, safety & security & functionality of the house. But they are willing to settle for cheaper and less-preferred alternatives. They are willing to cut back on the frequency and quantity of their purchases, but they focus on values such as safety, security, freedom &, etc. Moreover, their major motivation for housing was identified as the safety & security of housing which is a viable house with basic needs. They have a positive attitude towards housing with high utility rather than the abstract values of housing. Further, they have given a very low level of importance to the status & prestige needs of housing where only the ownership was given priority in expressing their social status or position. Therefore, the study clearly shows the current socio-psychological characteristics of the user which have been influenced due to current economic conditions. Contrarily to the existing literature about this consumer group, the research outcome shows a different perspective which is an emotional reaction due to the current market behaviour.

According to the results of the study, it has given the socio-psychological outlook of the current housing demand of the study group. Housing is a major economic and social component in a city, it plays a significant role in achieving sustainable growth. Especially during a period with an economic crisis, it is vital to allocate and utilize the available resources effectively, because such decisions and use of knowledge on demand can directly influence the sustainability of social life in a city. The insufficient utilization of resources in supplying housing not suiting the current demand can have high negative impacts on the city's sustainability and growth. Therefore, going forward, such information about changes & trends in the market can be used effectively to support in utilizing and allocating finances, and resources sustainably. Nevertheless, to understand the vitality of such information, it is very important to continue further research on these findings to get a more in-depth understanding by analyzing long-term market changes and trends and the durations and patterns of such periods in the market.

Acknowledgments
I would like to extend my sincere gratitude to my supervisor, for his invaluable guidance and support given to me throughout the entire process of this research. Further, I would thank the course coordinators and the staff in the Department of Estate Management & Valuation, University of Sri Jayewardenepura for their continuous support during my degree program.

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CLIMATE-SMART ROOFING MATERIALS AND TECHNOLOGIES IN SRI LANKAN CONSTRUCTION INDUSTRY: SPECIAL ATTENTION TO EASTERN PROVINCE

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Abstract: This research centers on analyzing the usage of roofing materials mainly in the Eastern province of Sri Lanka by assessing the knowledge of climate-smart roofing technologies through identifying barriers and proposing strategies to overcome these barriers. The research findings disclose that asbestos cement roof sheets and clay tiles are the most widely used roofing materials in the region. When choosing roofing materials, the public looks at factors such as indoor comfort, energy efficiency, and durability. The emerging climate-smart roofing materials and technologies can guarantee increased human comfort, low or non-toxic materials, waste reduction, improved indoor air quality, pollution prevention, reusability, recyclability, longer lifespan, and superior performance. However, several impediments hinder the widespread adoption of climate-smart roofing materials and technology. These barriers include a lack of awareness, higher initial costs, a lack of professional knowledge, a lack of demonstration and technology, and inadequate research investments. To overcome these barriers, strategies such as increasing public awareness, enhancing people's knowledge, promoting education and training, encouraging government leadership, nurturing collaboration among authorities, and supporting research and development are proposed. The research methodology integrates a comprehensive literature review, field observations, data collection, interviews, and questionnaires. Statistical analysis using SPSS was conducted, revealing a significant correlation between the number of qualitative variables. In conclusion, this research highlights the need to promote the adoption of climate-smart roofing materials and technologies in the Sri Lankan construction industry. By understanding the prevalent usage, and industry knowledge, and overcoming barriers through effective strategies, the outcome suggests that the industry can progress toward sustainable and environmentally friendly roofing practices.

Keywords: Climate-smart roofing materials and technology; Sri Lankan construction industry; Eastern Province; Barriers and challenges; Adoption and promotion

1. Introduction

Climate-smart roofing materials and technologies refer to sustainable and energy-efficient roofing systems that are designed to mitigate the impact of climate change on buildings and reduce their carbon footprint. These materials and technologies aim to minimize the energy used for cooling and heating buildings, reduce greenhouse gas emissions, and improve overall energy efficiency.

By using climate-smart roofing materials and technologies, buildings can reduce their reliance on non-renewable energy sources and reduce their carbon footprint. Cool roofs, for example, reflect sunlight and heat away from the building, reducing the amount of energy needed to cool the interior. This helps reduce the urban heat island effect, which can lead to higher temperatures in urban areas.
Climate-smart roofing materials come in a variety of styles, including:

Cool roofs: These roofing materials are designed to reflect heat and sunlight from the building. They are often made from materials like shingles, tile, or metal that is white or light-colored. By reducing the amount of heat absorbed by the building and hence the requirement for air conditioning, cool roofs can assist in reducing energy consumption.
Green roofs: These are roofing systems that are covered in vegetation, such as grass, plants, or trees. They provide excellent insulation, absorb rainwater, and help to reduce the urban heat island effect. Green roofs can also help to reduce energy consumption by providing natural insulation during colder months.
Solar panels: These are roofing materials that contain solar cells that convert sunlight into electricity. By producing renewable energy that may be utilized to power the building, they can help in reducing energy use. As solar technology becomes more affordable, solar panels are becoming more and more common.
Recycled materials: These include materials like recycled plastic, metal, or rubber, which are used to create long-lasting and durable roofing materials.
Insulated roofing materials: These materials are designed to provide greater thermal insulation, lowering the amount of energy required to heat and cool the building. These materials typically consist of a layer of insulation material such as foam sandwiched between two layers of roofing material such as metal, shingles, or tiles. The insulation layer helps prevent heat transfer from outside to inside the building during hot weather and from inside to outside during cold weather. This can help reduce heating and cooling costs and improve overall energy efficiency.

Aim

The research aims to highlight why the roof should be climate-smart and, if not, the impact of climate change, especially the issue of solar radiation, infrared radiation extreme rain, and wet weather, will damage the construction and eventually bring dissatisfaction to customers and a bad name for contractors.

2. Objectives

Main objective:

To identify the types of roofs currently in use and recommend suitable roof technologies considering the effects of climate change.

Specific objectives:

To examine the advantages and disadvantages of climate-smart roofing material and technology.
To identify barriers to the implementation of this technology and provide solutions.

3. Methodology

3.1 Identify the research area.

I'm interested in construction-related subjects. So, considering the topic was selected for the final year individual research project.

3.2 Identify the research problem.

This research enables us to evaluate the contractors more accurately. Specifically, their attitudes and resources to implement CSRAT practices, the knowledge, and internal capabilities to respond to their customers' pressures, and finally the strategies they are using to overcome the barriers.

3.3 Literature Review

A pool of research articles, older research related to CSRAT in the CI, or related to the components of the topic, including the definition, concepts, dimensions, and elements, as well as the key performance of CSRAT in the CI were carried out through the online library, Google Scholar, and relevant websites were used for the literature reviews.

3.4 Data collection

It is the most important component of research methodology. This research will follow the primary data collection method which can be divided into two groups such as quantitative and qualitative. The quantitative data collection method is based on mathematical calculations in various formats. It includes questionnaires with closed-ended questions, methods of correlation and regression, mean, mode, median, and others. Also, it is more comfortable to apply within a shorter duration of time compared to qualitative methods. Moreover, due to a high level of standardization of quantitative methods, it is easy to make comparisons of findings.

Data will be collected from Engineers, Assistant Engineers, Technical - officers, Technical Assistants, Managers, foremen & etc. through the questionnaire.

Types of Sampling: It can be categorized into Probability and Non-probability sampling. This research has chosen the probability sampling method, namely the Stratified sampling. In which the researcher divides the population into subgroups that do not overlap but represent the entire population.

Sample size: Yamane (1967:886) provides a simplified formula to calculate sample sizes. This formula was used to calculate the sample sizes.

$$n = \frac{N}{1 + N\varepsilon 2}$$

n= Minimum returned sample size

N = the population size = 108 (Total Building construction companies in eastern province)

https://www.cida.gov.lk/sea_con/middlewithadd.php?typea=MA

$$\varepsilon = \text{adjust margin of error } (\varepsilon = \frac{\rho e}{t}) = \frac{2(0.05)}{1.96} = 0.051$$

ρ= the number of standard deviations = 2

e = the degree of accuracy expressed as a proportion = 0.05

t= t-value for the selected alpha level of confidence level at 95% =1.96

$$N = \frac{108}{1 + 108(0.051)^2}$$

According to this equation, I have 84.31 so the minimum returned sample size is 85.

4. Data Analysis

Relative Important Index (RII): It is a mean score for each item & that will shorten items from "most" to "least". Here RII was calculated for the elements of independent variables. Data will be analyzed with the help of the software (MS Excel).

$$\mathrm{RII} = \frac{\in W}{A \times N}$$

Table 1: Advantages of climate-smart roofing material and technology

Advantages	**RII**	**Rank**
Reusability	0.741176	6
Recyclability	0.708235	7
Pollution Prevention	0.743529	5
Waste Reduction	0.752941	3
Longer life	0.670588	8
Low or non-toxic	0.854118	2
Increase the human comfort	0.905882	1
Superior	0.647059	9
Indoor air quality	0.750588	4

Table 2: Barriers to using climate-smart roofing material and technology in the construction industry.

Barriers	**RII**	**Rank**
Lack of Awareness	0.856470588	1
Lack of Professional Knowledge	0.750588235	3
Lack of Research Investments	0.635294118	5
Lack of Demonstration and Technology	0.710588235	4
Higher Initial Cost	0.804705882	2

Table 3: How can Reduce the barriers?

How Can We Reduce the Barriers	**RII**	**Rank**
People's level of awareness about Climate smart roofing material and technologies	0.769411765	2
Make collaboration between the existing authorities	0.696470588	5
Increase public awareness	0.809411765	1
Promote Knowledge and education	0.717647059	3
Promote Research and development	0.687058824	6
Government take leadership	0.710588235	4

5. Conclusion

In conclusion, the research objectives of the study aimed to analyze - age of roofing materials, assess the knowledge and advantages of climate-smart roofing materials and technologies, identify barriers, and propose strategies to reduce these barriers in the Eastern Province of Sri Lankan construction industry.

Based on the findings, it was observed that asbestos cement roof sheets and clay tiles were the most widely used roofing materials among the population. The knowledge of the construction industry regarding climate-smart roofing materials and technologies was influenced by factors such as environmental benefits, improved indoor comfort, energy efficiency, and durability. The advantages perceived by the industry included an increase in human comfort, low or non-toxic materials, waste reduction, improved indoor air quality, pollution prevention, reusability, recyclability, longer lifespan, and superior performance.

The identified barriers to the use of climate-smart roofing materials and technology included a lack of awareness, higher initial cost, lack of professional knowledge, lack of demonstration and technology, and inadequate research investments. To address these barriers, strategies such as increasing public awareness, enhancing people's level of awareness, promoting knowledge and education, encouraging government leadership, fostering collaboration between existing authorities, and promoting research and development were proposed. Overall, the study highlights the need for further research in the field of climate-smart roofing materials and technologies, particularly in different regions and grades of construction. It emphasizes the importance of addressing the identified barriers and promoting the adoption of climate-smart roofing materials and technologies to benefit small-scale construction firms and new entrants in the industry. By considering the prevalent usage of specific materials, understanding the knowledge and preferences of industry professionals, and implementing effective strategies, the industry can move toward sustainable and environmentally friendly roofing practices.

6. Recommendations

The different elements that influence climate-smart roofing materials and technologies in the construction industry have been investigated, and each of these usages has been examined. A study was carried out based on the perceptions of professionals involved in building projects. A questionnaire survey was carried out to collect data. Based on the available data, more professionals are opting for "Increase the human comfort" because of the numerous advantages.

According to the barriers, most of the professionals are selected with a "Lack of Awareness". Furthermore, according to the plan to reduce barriers, the majority of professionals choose to "Increase public awareness". It may depend on several factors as building design and the technology used. To address the issue of "lack of awareness" and increase adoption of climate-smart roofing materials and technologies among professionals in the construction industry, consider implementing the following solutions:

- Education and Training: Develop educational programs and training sessions to increase awareness about the benefits and usage of cli- mate-smart roofing materials. Collaborate with industry associations and educational institutions to provide accessible and relevant training opportunities.
- Information Dissemination: Establish a communication strategy to provide easily accessible and up-to-date information on the advantages, costs, and installation process of climate-smart roofing materials. Use websites, brochures, and industry publications to effectively communicate information.
- Demonstration Projects: Create demonstration projects to showcase the benefits of climate-smart roofing materials. Organize guided tours and hands-on experiences for professionals to foster a deeper understanding of their practical applications.
- Collaboration and Partnerships: Foster collaboration between professionals in the construction industry, industry associations, research institutions, and government bodies to collectively address the lack of awareness. Organize conferences, seminars, and forums for professionals to share experiences and learn from successful case studies.
- Incentives and Recognition: Provide financial incentives, such as tax breaks or grants, for

projects that incorporate climate-smart roofing materials. Establish recognition and awards programs to acknowledge professionals who actively promote and implement these solutions.

By implementing these solutions, you can effectively tackle the "lack of awareness" barrier and encourage professionals to embrace climate-smart roofing materials and technologies.

At the same time, it is important to consider the cost associated with climate-smart roofing materials and technology. The costs can vary depending on various factors including location, material quality, installation requirements, and project size. Here is a general overview of the cost range for some commonly used climate-smart roofing options:

1. Cool Roof:
- Cool roof coatings: Approximately 230.29 to 767.62 LKR per square foot of roof area.
- Cool roof membranes: Approximately 461.43 to 1,535.25 LKR per square foot.

2. Green Roof:
- Extensive green roofs: Approximately 3,070.50 to 7,676.25 LKR per square foot.
- Intensive green roofs: Approximately 7,676.25 to 15,352.50 LKR per square foot or more.

3. Solar Panels:
- Photovoltaic (PV) solar panels: Approximately 767.62 to 1,229.00 LKR per watt of installed capacity.
- Solar thermal panels: Approximately 460,875 to 1,228,300 LKR per panel.

4. Recycled Materials:
- Costs for recycled roofing materials, such as recycled metal or rubber shingles, can be comparable to or slightly higher than traditional roofing materials. Prices vary depending on the material type and quality.

5. Insulated Roofing Materials:
- Insulated roofing panels: Approximately 1,228.30 to 3,070.50 LKR per square foot.
- Insulated roofing membranes: Approximately 921.23 to 2,456.40 LKR per square foot.

It's important to note that these cost ranges are approximate and can vary significantly based on specific project requirements, geographical location, contractor rates, and market conditions. Additionally, costs may evolve due to advancements in technology, economies of scale, and changing market dynamics.

To reduce costs associated with CSRAT, various strategies can be employed for each of the factors mentioned in the cost analysis. Here are some strategies for cost reduction:

Initial Costs:
- Seek competitive pricing from multiple suppliers to ensure the best value for the materials and equipment needed.
- Explore bulk purchasing options or group-buying arrangements to negotiate lower prices.
- Consider alternative financing options, such as leasing or financing programs, to spread out the initial cost over time.
- Look for government incentives or grants that provide financial support for implementing climate-smart roofing materials and technology.

Maintenance and Repair Costs:
- Implement proactive maintenance strategies, including regular inspections and cleaning, to

identify and address issues early on, reducing the need for extensive repairs.

- Train staff or engage specialized contractors to perform routine maintenance tasks in-house, reducing outsourcing costs.
- Utilize durable and long-lasting roofing materials with minimal maintenance requirements to minimize ongoing expenses.

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IMPACTS OF SUSTAINABLE GREEN HIGHWAYS CONSTRUCTION ON THE ECONOMY OF SRI LANKA: A SYSTEMATIC LITERATURE REVIEW

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Abstract: Sustainability is a very popular and important concept nowadays. Highway construction has the potential to directly impact the environment, economy, and society of a country. Transportation authorities have begun developing sustainability rating systems that attempt to quantify sustainable design practices and elements of transport infrastructure. The "green highway' is a new concept that can be implemented when developing any road construction. Moreover, the construction sector is one of the majors which contributes to the GDP of Sri Lanka over the past decade. Considering the point, that Sri Lanka is a developing country, and facing an economic crisis, the traditional highway construction methods create a massive negative impact on the economic development of Sri Lanka. Accordingly, the price of construction materials along with other construction-related services has rapidly increased, therefore, it has become much more challenging to complete highway construction. Consequently, this research aims to figure out specific impacts on the economy of Sri Lanka by implementing the green highway concept in highway construction, through three main objectives; Identify the differences between the current practice of highways and sustainable green highways, Recognize the existing sustainable green highway methods in the world and identify the economic impact of the above methods to the Sri Lankan context. In addition, a systematic literature review has been done using one hundred fifty past research studies. Furthermore, this research paper provides an analytical comparison between the impact of traditional and sustainable green highway construction in Sri Lanka.

Keywords: Green highway; Construction; Economy; Sri Lanka

1. Introduction

The construction industry plays a crucial role in a country's economic growth. (Hussin,J.M. ,Rahman,I.S. and Memon,A.H., 2013). Building construction, road construction, irrigation work, infrastructure, and refurbishments are the works that are related to the construction industry. Improvements in transportation infrastructure would allow people and goods to flow across the country more efficiently. Therefore, highway infrastructure holds a significant place within a country's economy. Not only highway construction, but all construction-related activities also generate the highest level of greenhouse gas emissions, a ton of wastage, habitat destruction, deforestation, air pollution, noise pollution, and many more negative impacts. It is a big challenge that the construction sector is facing in this century. Hence, it is crucial to mitigate the above-mentioned negative effects through proper planning and implementation of sustainable construction practices. Then the "green highway" concept rose to prominence due to its innovative and eco-friendly approach toward highway infrastructure. The green highway is a new roadway design concept that integrates transportation functionality & ecological sustainability. According to Nusa et al (2015), it is essential to be able to quantify the importance of the green highway rating system and green highway initiatives to minimize the pollution to the environment, zero or low greenhouse gas emissions, a safe highway for use, and promote healthy, conserve the energy usage and natural resources, and promote the use of renewable resources.

Sri Lanka is a developing country, and the construction sector contributes to the improvement of the country's economy, enhancing Gross Domestic Product (GDP) and offering considerable employment opportunities over the past decade. De Silva, S.S., Wijekoon, S.S. and Kalugala, C.S., (2023) stated that the construction industry's contribution to Sri Lanka's GDP has shown consistent growth with a recorded contribution of 6.1% in 2016, followed by subsequent increases of 7.2% in 2017, 6.8% in 2018, 6.9% in 2019, and 6.2% in 2020. Currently, Sri Lanka is facing a massive economic crisis. The foreign exchange reserves have been significantly depleted. The COVID-19 pandemic, taking a huge amount of foreign loans, corruption, and misgovernance are a few reasons for this economic crisis. It became a severe problem for all the sectors including construction. Nandy, D., Al-Mamun, A. and Akon, S., (2023) determined that the GDP of the country has been remarkably reduced since 2020. In addition, the price of essential materials and goods has rapidly increased and during the pandemic, the supply chain has been disrupted. Furthermore, the value of the Sri Lankan currency depreciated by 4%. That affected significantly all the sectors of the country & and all the sectors are still going through this challenging period. Therefore, this presents a favorable opportunity to tackle the economic crisis, advance the cause of "green highway" construction for future highway projects in Sri Lanka, and fully harness its benefits.

This paper is focused on previously published research findings on sustainable infrastructure and specific impacts on the economy. A systematic literature review has been done using one hundred fifty past research studies. This research aims to get new ideas and knowledge that could be useful for future studies on making sustainable concepts in highway construction. Furthermore, the study has explored "green highway" construction and how to apply this concept and sustainable highway construction methods in the Sri Lankan context. The research is based on three main objectives (1) Identify the difference between the current practice of highways and sustainable green highways. (2) Recognize the existing sustainable green highway construction methods in the world & and identify the economic impact of the above methods on the Sri Lankan context. (3) Comparison between the impact of traditional and sustainable green highway construction. In summary, this study strives to bridge the gap between sustainable construction practices and the economic challenges faced by Sri Lanka. By exploring the green highway concept and its potential benefits, the research seeks to lay the groundwork for the integration of sustainable principles, and techniques into future highway projects, thereby fostering economic recovery, environmental preservation, and overall national well-being.

2. Methodology

Research was conducted using one hundred fifty published papers, and journal articles related to sustainable construction and subsequently, within the selected papers, again filtered the papers focus on sustainable green highway developments. Data was collected through the examination of the fifty most pertinent articles authorized by various individuals.

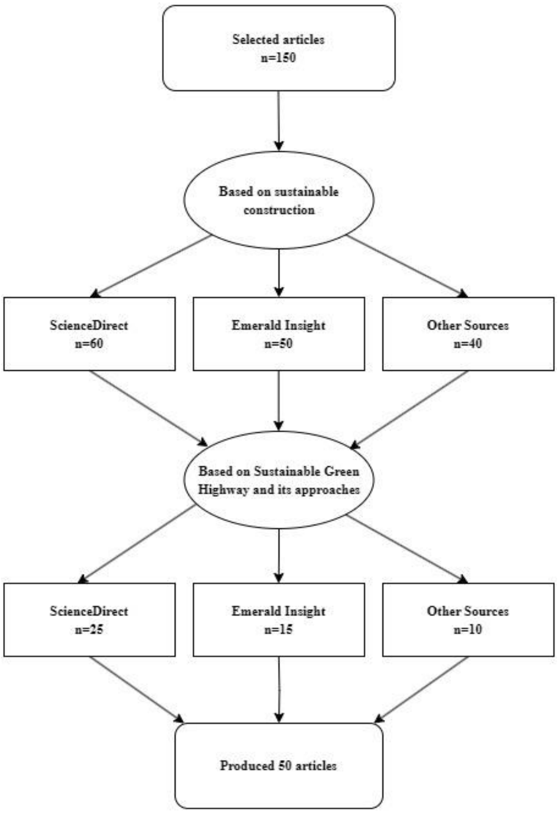

Figure 1: process of paper selection.

3. Literature Review

3.1 The notion of green highways

The concept of sustainability has gained popularity in the construction industry due to heightened awareness of environmental challenges like climate change and resource depletion. Public demand for environmentally conscious projects and the potential for long-term cost savings through energy efficiency further contribute to its appeal. Sustainable development is to make the world a better place for everyone without destroying the possibilities for the next generations. Constructing highways requires a huge materials and energy consumption, including things like rocks, asphalt, concrete, steel, and many more. Unfortunately, many of these resources are non-renewable and cannot be replaced easily. This means that building highways can have a significant impact on the environment, economy, and society of a country. (Liu,H.,Chen,J.and Zhang,D., 2022). It is essential to understand how these factors are connected and how highway construction can affect a nation’s overall well-being and development. Subsequently, the “green highway “concept was introduced to promote the exploration of alternative methods that would minimize the ecological footprint of highway infrastructure development.

Nusa et al, (2015) stated that the definition of the green highway itself is different from the perspective of each researcher and organization body. A “green highway” signifies a roadway that establishes a balanced and symbiotic relationship between traffic and external elements. These external factors encompass not only the ecological aspects but also extend to energy considerations, social, economic, and various other dimensions. “Green highway” road design integrates transportation functionality and ecological sustainability. (Liu,H.,Chen,J.and Zhang,D., 2022)

Though conventional highway construction only focuses on time, cost, and quality aspects, sustainable highway construction emphasizes the minimization of resource depletion, minimization of environmental degradation, and improve the well-being of the environment and society. Hussin, J.M., Rahman, I.S., and Memon, A., (2013) pointed out that sustainable green highways prioritize three significant aspects which are economic sustainability, environmental sustainability, and social sustainability.**1.** Economic sustainability in highway construction refers to the ability to enhance its economic well-being over the long term involves making decisions and taking actions not only focusing on profit and financial benefits but also considering the efficient use of resources including labor, materials, water, and energy. The ultimate purpose of this is to ensure that economic activities remain viable and beneficial while reducing waste and negative impacts on the environment and society **2.** Environmental sustainability is the practice of using natural resources and engaging in construction-related activities in a way that can enhance the well-being of the environment. Many natural ecosystems must be in balance to live on the planet. The climate system can be considered as one of them. The climate system ensures the temperature is at a certain level and that the atmosphere precisely emits the right amount of solar energy. The development of highway construction involves some sort of harmful activities, and because of that greenhouse gases are released into the atmosphere. When emitting harmful greenhouse gases such as CO_2, and NO_2 into the atmosphere, it clogs the atmosphere and leads to changes in the temperature which again affects the development of highway construction. Therefore, it is essential to approach the planning, design, and construction of highway projects to minimize the pollution of the environment through environmental management strategies. **3.** Social sustainability mainly focuses on the well-being of society, achieving equitable benefits from planning the operation of highway transportation that is environmentally friendly and sustainable. The purpose of considering social sustainability in the green highway concept is to ensure that the creation and functioning of environmentally friendly highways have the potential to affect society and nearby communities. Competitive factors in traditional highway projects (time, cost, quality) are interconnected with each other and play a crucial role in the success of any conventional construction project. With the global popularity of the “green highway” concept, economic, environmental, and social sustainability are incorporated as additional dimensions to the competitive factors to the success of green highway projects. (Hussin,J.M. ,Rahman,I.S. and Memon,A.H., 2013)

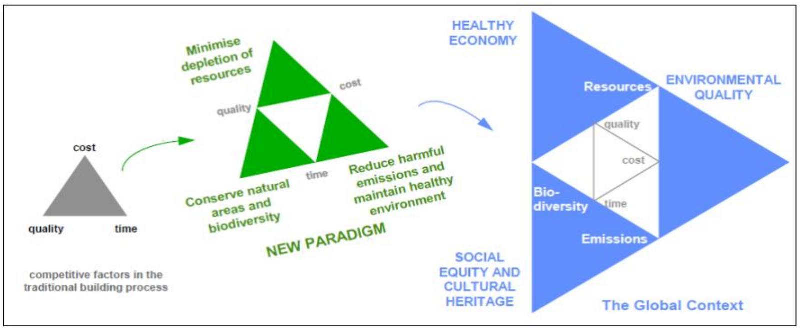

Figure 2: New paradigm of a successful construction project (Hussin J.M.,Rahman I.S. and Memon A.H., 2013).

A sustainable approach seeks to meet all the above-mentioned needs while working to achieve economic goals for cost-effectiveness throughout a highway’s life span. Further, the Federal Highway Administration stated that their perspective of sustainable highways as a “sustainable approach to highways means decision-makers can make balances and efficient choices among environmental, economic, and social values -the triple bottom line of sustainability- that will provide the benefits to the natural and human environment now and in the future.”

Figure 3: The Sustainability Triple Bottom Line (Transportation, 2014).

3.2 Key components of green highways

A green highway should fulfill specific key areas to ensure its environmental sustainability and positive impact. All five key areas compass must achieve successful green highway development. (Bryce, 2008)

Figure 4: Five key areas of Green Highways (Bryce, 2008).

3.2.1 Watershed-driven stormwater management

Watershed-driven stormwater management is important in mitigating the impact of stormwater runoff from highways and contributes to overall environmental sustainability. This method focuses on understating and overseeing that a highway covers areas, making it possible to reduce the runoff that exists on the road during rainfall events. Nusa et al, (2015) further explained that it is the process of managing the runoff water to the place where the water can be infiltrated into the groundwater table. The purpose of adopting this method is to reduce the amount of water entering neighboring waterways such as rivers, lakes, and oceans while also ensuring that the runoff is adequately treated before it enters natural systems. Bio-slopes, bio-swales, bio-retention cells, permeable pavers, vegetable filter strips, and street trees are a few examples of watershed-driven stormwater management technologies used in highway construction, according to Nusa et al, (2015) These technologies are widely used in United States, reflecting a concerted effort to establish practical yet cost-effective solutions through meticulous design and assessment for stormwater management along highways.

3.2.2 Lifecycle Energy and Emissions Reduction

Energy plays a crucial role in the economy, and the development of highways requires a large amount of energy. The production of materials like asphalt and cement for use in highway road surfaces, and excavation of materials used a significant amount of energy. Energy is not solely a requirement during the highway's construction phase; it also plays a pivotal role in its maintenance over time. Moreover, the ongoing upkeep of roads and energy expended by vehicles stuck in traffic on not properly planned highways contributes to this energy-intensive cycle. There are numerous practices on highways to reduce the lifecycle energy consumption. These practices aim to reduce emissions and enhance the quality of the air. For instance, Bryce, (2008) stated that the US Department of Transportation's (DOT) research center and Innovative Technology Administration collaboratively are creating a method of using warm mix asphalt in place of hot mix asphalt. The research method explored that the warm mix of asphalt, owing to its requirement for lower production temperature, will result in a notably reduced energy consumption compared to hot mix asphalt.

Cement is another vital material that is extensively used in highway projects and the production of cement generates a lot of energy consumption. USEPA (United States Environmental Practice Agency) has researched materials to replace a large portion of cement which is called pozzolans, consisting mainly of by-products from steel plants and coal combustion facilities. It is responsible for highway engineers and other professionals to avoid or mitigate a lot of energy consumption and emissions through proper planning designing and implementing strategies. (Bryce, 2008)

3.2.3 Recycle, reuse, and renewable

The use of recycled, reused, and renewable materials is another key aspect of green highway road construction. Using recycled materials in highway design can have an impact, leading to a significantly decreased volume of materials being deposited in local landfills. Furthermore, this practice contributes to a reduction in the necessity for virgin material extraction sites during highway construction. The concept of green highway focuses on promoting and expediting the extensive adoption of recycled materials. This initiative has led to the utilization of various industrial by-products such as blast furnace slag, fly ash, bottom ash, boiler slag, reclaimed payment materials, anthracite coal waste, and many other industrial by-products for the constructive purpose of highway development as the evidenced by the research conducted by Edil, (2006). Nusa et al, (2015) the paper further described that another benefit of recycling, reusing, and utilizing renewable materials in highway construction lies in the enhancement of conservation, alongside a reduction in both carbon and air emissions. In some instances, a by-product has not matched the quality of conventional earthen materials, yet its affordability renders it an appealing substitute, especially if it can deliver satisfactory performance levels. (Edil, 2006)

3.2.4 Conservation and Ecosystem Management

Conservation and ecosystem management play an important role in green highway construction. The presence of highway systems influences various facets of the ecosystem. One of the most prominent outcomes of highways on the natural environment is the disruption and fragmentation of natural habitats. Other adverse impacts on wildlife become apparent when their natural water flows close to a highway. The excess surface runoff from the highways leads to erosion of the riverbed and consequent expansion of the stream channel. The channel widening, coupled with the reduction of the natural groundwater table due to the increase in impermeable surfaces associated with highways, can be caused by periods of notably diminished water flow, and some problems, complete cessation of flow in streams. Numerous strategies can be implemented to mitigate ecological system disturbances, and can likewise, be harnessed for managing stormwater based on watershed considerations. Wetlands and bio-swales are both water treatment techniques that will also help decrease the excess runoff water from highways, while simultaneously countering the scoring effects on streams. Additionally, these techniques offer a valuable function in the realm of natural water treatment. (Bryce, 2008)

3.2. 5 Overall societal benefits

Over many years, the concept of sustainability has primarily centered on its application within the natural environment, occasionally sideling its effects on the constructed environment. However, a more comprehensive perspective on sustainable construction dictates considerations of broader societal benefits. Highways wield a significant influence on local economics. Well-planned highway design can draw businesses into a community by providing employment opportunities and generating tax revenue for the government. (Bryce, 2008)

3.3 Existing methods and techniques used in green highway construction.

The sustainable green highway is paramount in the world where carbon dioxide emissions and rising sea levels are notable concerns. Among the sectors, the road construction sector significantly contributes to carbon emissions and global warming. Therefore, highway engineers and other responsible professionals are responsible for promoting and implementing sustainable methods and techniques within highway construction to address the above-mentioned issues. There are numerous sustainable methods and techniques which are implemented in existing green highway developments.

3.3.1 Use lower carbon materials

Most of the roads are made from asphalt which is derived from petroleum. The production of asphalt is associated with the emission of greenhouse gases into the atmosphere. The most effective method to reduce greenhouse gas emissions related to asphalt involves adopting lower-carbon materials such as recycled plastics or wood waste. Comparatively, these materials are more environmentally friendly than concrete reduce emissions and are more durable in the long run. (Kolk, 2022)

3.3.2. Use 1ower carbon concrete

Concrete is most widely used in the construction industry. Concrete is highly comprehensive and can withstand any weather conditions. It has the potential to provide good riding when trucks carry freight or vehicle, transportation passengers. The production of concrete involves high energy consumption and a huge amount of carbon dioxide emissions associated with it. Fly ash and slag are alternative materials for cement. This can help to reduce harmful emissions and provide more eco-friendly highway infrastructure.

3.3.3 Warm mix asphalts

Kolk, (2022) explored that using mixed asphalt can reduce carbon dioxide emissions in highway construction which is an innovative approach to green highway development. Mix asphalt contains fewer aggregate materials and has the potential to diminish paving costs alongside enhancing the quality of the environment compared with conventional cold mixes. Competitively, warm mix asphalt generates fewer greenhouse gases and notably reduces noise pollution during construction. Conventional asphalt mixes require more bitumen than warm mix asphalt, warm mix asphalt reduces the production energy and carbon footprint.

3.3.4. Energy-saving asphalt

Asphalt is one of the most environmentally damaging road surfacing materials in the world. The life expectancy of asphalt is about twenty years, necessitating it must be removed and replaced with new asphalt. According to Kolk, (2022) as a result, up to 65% of the original asphalt content finds its way to landfill or incineration. Material sustainability is taking a significant place because it helps to reduce carbon footprint and it's an effective method to help slow climate change. As a sustainable approach, developed an asphalt mixture that uses comparatively less cement, which decreases carbon emission during production by up to 50% by the Rice team. To increase durability, they added silica fume which is formed as a waste product from steel mills that is used as an alternative for cement thereby strengthening the mixture's binding properties.

3.3.5 Sustainable Drainage System

The drainage system is a critical aspect when developing any highway construction**.** Sustainable drainage systems don't require regular cleaning and maintenance work as conventional drainage systems. Sustainable drainage systems have been designed to filter out debris before it can enter the primary drainage system. These practices are more eco-friendly, and they reduce stormwater pollution and flooding.

3.3.6 Use permeable pavers

Using permeable pavers in highway development can reduce runoff and pollution by facilitating the absorption of rainwater into the ground instead of collecting storm drains. This is an innovative approach to decreasing road maintenance costs. (Kolk, 2022) In addition, some countries are experimenting with using recycled plastic in road construction. The plastic is melted down and mixed with asphalt to create a durable and long-lasting road surface. This approach helps reduce plastic waste while creating a strong and resilient road. The use of geosynthetics is another innovation in road construction such as geotextiles and geomembranes which can provide additional reinforcement and drainage for the road. These materials are cost-effective and can extend the road's lifespan.

3.4 Green Highway Rating System

Highway construction activities can directly affect the degradation of the environment. The green highway rating system is the tool to measure the performance of green practices throughout the life cycle of the highway project. The concept of a "green highway rating system" has been developed to mitigate noteworthy environmental impacts and to promote greening and the development of eco-friendly highways (Bryce, 2008). Since Sri Lanka has not developed a green highway practice there is no green highway rating system yet. Many standards have been developed to focus on green highways which are INVEST (Infrastructure Voluntary Evaluation Sustainable Tools); ENVISION (Sustainable Infrastructure Rating System); Green Road Rating System; GreenLITES(Green Leadership In Transportation And Environmental Sustainability); BE2 ST-in-Highways; and I-LAST(Illionois-Livable and Sustainable Transportation. As mentioned all green highway rating systems focus on specific areas including energy efficiency, energy and atmosphere considerations, project lifecycle assessment, water management, energy efficient wastewater management, utilization of recycled materials, and efficient lighting solutions. The standard rating system plays a crucial role in green highways that can help enhance the quality of highway infrastructure and a better living environment. (Nusa et al, 2015)

3.5 Transformation of conventional highways into green highways

Environmental disruption and the usage of huge amounts of energy and resources were the significant influences when implementing any construction, until a few decades ago. However, the responsible professionals did not take it as seriously in the construction industry and did not take any action against those issues. The depletion of natural resources and the effect of climate change has become a severe problem around the world. Then all the construction organizations around the world intended to adopt more sustainable approaches to address those pressing issues. Consequently, the notion of the green highway was introduced, and most Europe countries are adopting greener strategies for their highway projects instead of conventional highways to achieve efficiency and eco-friendly transportation.

3.5.1 Comparative analysis of conventional highway construction and green highway

When comparing the differences between traditional highway construction and sustainable green highway construction most specific thing is that sustainable green highway construction emphasizes the use of recycled materials, and renewable energy consumption rather than relying only on virgin materials like asphalt, and concrete alongside the use of non-renewable energy. Hence, fewer resources need to be extracted from the earth and reduced carbon emissions produced by mining operations lead to significantly reduced costs (Kolk, 2022) . Green highways, also known as eco-friendly sustainable highways, provide numerous benefits in terms of the economy, society, and the environment. Green highways focus on environmentally conscious practices in their planning, construction, and maintenance and that forwards to positive impacts. The development of the highway process utilizes a large amount of aggregate and asphalt materials. Substituting natural soils, aggregates and cement with industrial by-product materials is one of the approaches that are used in green highways to enhance sustainability. conventional highways are not implementing these practices within the development. When applied re-use and recycling methods lead to significant positive benefits such as minimizing the disposal of excess materials, conservation of natural resources materials, curbing energy usage, and reduction of environmental pollution. Moreover Kehagia, (2009) pointed out that technology plays a major role in sustainable development, and it is one of the ways to interact with the environment. To achieve economic development and human satisfaction in harmony, sustainable technology practices are important. This technology has the potential to contribute to advanced green highways by reducing risk, enhancing cost-effectiveness, and engendering the creation of processes. A new process needs to be adopted to redirect conventional highway construction toward sustainability. Kehagia, (2009) emphasized that environmental technologies, natural resource management, waste management, and minimization of environmental impacts have been added to the traditional construction approaches for green highway development. Green technology involves the development of green highways. Green technology is the one that helps reduce greenhouse gas emissions, conserve natural resources, reduce waste, and consume less energy than conventional technology.

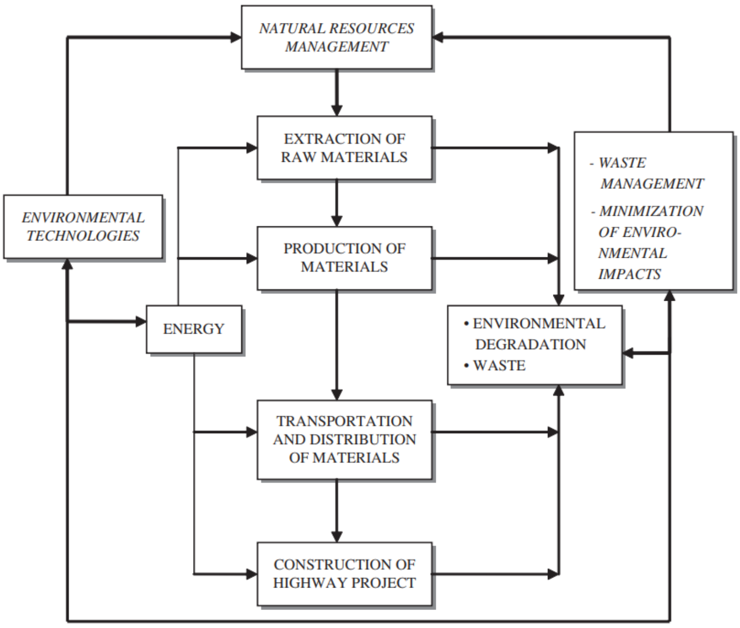

Figure 5: The framework of a green highway construction process (Kehagia, 2009).

3.6 Economic dimension of green highways

Earlier, when developing highway construction there was only a focus on economic grounds and criteria. After introducing the green highway concept, the construction sector considers more than economic grounds and criteria when developing a highway. Green highways can directly affect the economy of a country. Poverty reduction is the systematic effort to improve the economy, thereby boosting living standards. Poverty is a prevalent challenge in both developed and developing countries, but significantly more common in developing countries than in developed countries. Capital, personal accounts, land worth, infrastructure, medical status, and educational background are the indicators that can measure poverty reduction. Then the green highway can be used as an innovative solution to address poverty reduction. Green highways can have positive impacts on commercial activities and assist the creation of new communities. A huge amount of fuel consumption associated when developing a highway, thereby substantially harmful greenhouse gases released into the atmosphere. The use of biofuels such as biodiesel and ethanol emit fewer greenhouse gases due to their insignificant sulfur content and less amount of carbon monoxide (CO), carbon dioxide (CO2), and nitrous oxide(N2O). This approach has the potential to contribute to economic growth and thriving communities. Curbing greenhouse gases by adopting renewable energy sources in highway construction can significantly reduce the cost of the highway project. When constructing highways, the transition from fossil fuel to renewable energy has the potential to mitigate notably negative impacts of climate change, in addition to generating substantial economic benefits (Attahiru et al., 2019). Skilled and unskilled laborers are required to complete the highway construction, providing job opportunities can improve the economy of a country alongside helping to enhance an individual's well-being. use local natural resources, promote the use of renewable materials, local labor force, zero or low greenhouse emissions, and conserve energy are the considerable key aspects of green highway construction thereby stimulating economic activity within the country. Therefore, demand for local goods and services increases, and that can help entrepreneurs boost their businesses and the overall economic development of the country. Innovation and technology are prominent aspects of green highway development which often involve the use of innovative technologies and materials. Innovation encourages the creation of innovative solutions within the country, and it contributes to economic growth. Energy efficiency, durability, and reduced maintenance are mainly focused areas of green highway construction. When developing green highways, initial investment might be higher than operational and maintenance costs, however, it is cost-saving for the government. Improvement of the highway infrastructure can stimulate economic growth by attracting tourists and the intention to invest. Tax revenue can be obtained for the government through sustainable green highway projects. Any type of construction should be more resilient, and strong enough to withstand any kind of natural disaster and extreme weather, resulting can reduced infrastructure damage and associated repair costs. A country's international reputation can be enhanced through sustainable infrastructure projects that attract foreign investment and partnerships and lead to further economic growth. (Attahiru et al., 2019)

Addressing green highways as an innovative solution to the economic challenge in Sri Lanka

Sri Lanka is an island located in the Indian Ocean near to southern coast of India. The Sri Lankan economy is based on agriculture, industry, and services. Construction has been a significant contributor to the economy. Construction is the fourth largest sector that contributes to the economy of Sri Lanka, which contributed about 6%-7% of the GDP of the country in the last decade, as evidenced by the research conducted by Karunarathne, (2021). In the construction sector, the development of highways plays a crucial role in improving the economy of Sri Lanka. Sri Lanka is a developing country, and it has been going through a massive economic crisis. Nandy, D., Al-Mamun, A. and Akon, S., (2023) as mentioned earlier several reasons caused the economic crisis. It became a severe problem for all sectors including construction. Further author has stated that consequently, the GDP of the country has been significantly reduced since 2020. In addition, the price of essential goods and services increased rapidly. Then it has become much more challenging to complete highway construction by applying conventional practices. Therefore, this study attempts to bring up the green highway concept to the Sri Lankan context to address the economic challenge as an innovative solution for ongoing and upcoming highway projects. However, the implementation of the green highway concept applied in road construction projects has not yet started in Sri Lanka.

Due to the increase in the price of materials, fuel, and services highway construction is in a difficult situation to carry out the projects. Many workers experienced unemployment due to the economic downturn that ensued in the country. Hence, it is essential to emphasize the necessity of job security and to recover the economic problems. Green highway approaches not only focus on the improvement of transportation but also consider ecological sustainability and economic resilience. The concept of green highway promotes local resource utilization that can minimize the negative environmental impact emphasizing reuse, and recycling principles within the country and that can have the potential to create a circular economy. Streamlining the process of recycling, reusing, and renewable green concepts the country can generate a multitude of job opportunities for the local community. Through optimization, this process results in cost savings for the country and can reduce unemployment rates. To enhance productivity, the local workforce should be encouraged to get the maximum benefits. This strategic approach has the potential to address economic issues when developing highways in the economically challenging period of the country.

Construction is a highly energy-consuming sector worldwide. A large amount of fossil fuel is used in highway construction. Fossil fuel is non-renewable energy that cannot be replenished in a short period. Fossil fuel takes significantly longer than millions of years to form. It is the largest emitter of carbon dioxide and other greenhouse gases which causes climate change. Therefore, the world has stepped up to go with alternative sources of energy. Currently, as a country, Sri Lanka is grappling with an economic crisis. Consequently, the fuel required for highway construction has to be brought to the country at a higher cost compared to the previous prices. It is a huge loss for the government. It becomes imperative to use alternative energy for fossil fuels within the country to complete highway projects successfully. Sri Lanka, which is blessed with natural resources, with its abundant solar energy throughout the year, and in some areas solar energy is received too much. the wind is another natural energy that is available in Sri Lanka. Involving some mechanisms these two resources can be converted as energy that can be used as a solution to an energy crisis. Solar energy is derived by capturing radiant energy from sunlight and converting it into heat or electricity. One of the benefits of solar energy is that it is available in Sri Lanka. The use of solar energy in highway construction could reduce energy costs. The wind is another natural resource that can be converted as an energy source. When farms capture the energy of wind flow by using turbines and converting it into electricity. Wind energy technology generates job opportunities, thereby also contributing to the economy of the country. Knowledge, meticulous planning, and effective management strategies are the key factors in implementing sustainable energy innovations in Sri Lanka and there should be a collaborative effort between the government and its citizens to engage these procedures. Sri Lanka is one of the most beautiful countries and it has been a tourist destination in the world. The country has a diverse range of ecosystems, such as rainforests, beaches, and wildlife reserves. According to Nandy, D., Al-Mamun, A. and Akon, S., (2023) tourism sector is also a leading sector that significantly contributes GDP of the economy of Sri Lanka while creating 250,000 direct and approximately two million indirect employment opportunities. The tourism sector has had a setback since April 2022 due to the unstable situation of the country. A new concept of green highway integrates with the plantation, Beautification, Replantation, and maintenance towards the sustainability of the highway. Promoting greening and the development of eco-friendly national highways is one of the key features of the green highway concept. The tourism sector has setbacks currently due to the unstable government, economic problems, and many more issues. The green highway concept has the potential to bolster tourist activity thereby implementing this concept in Sri Lanka can boost the economy by attracting more visitors. Implementing green highway approaches can be expressed as one of the strategies that can minimize economic obstacles to developing highway construction. Since Sri Lanka has not stepped up yet toward green highway construction, it is important that emphasize its economic value and significance of transportation functional and ecological sustainability and learn how to apply it to Sri Lankan highway construction projects now and in the future.

4. Conclusion

The research paper has focused on sustainable infrastructure and its significant importance. A systematic literature review has been done using past research papers and articles. Construction is a leading sector that contributes substantial GDP to the economy of the country. Developing any type of construction requires a lot of resources and energy which are generally non-renewable and cause negative impacts on the environment and human well-being. The sustainable concept has been introduced to address the above-mentioned challenges by implementing its practices. Green Highway is a new concept that focuses on minimizing pollution, reducing greenhouse emissions, conserving energy, and natural resources, and promoting the use of renewable resources towards sustainable highway development. By implementing this concept economic, environmental, and social benefits can be taken. Most of the developed countries and developing countries apply this concept to their infrastructure development instead of using conventional highway construction to get maximum benefits.

The paper has discussed the green highway concept and its components, green highway rating systems, and existing methods and techniques that are applied to highway developments. Further, the paper has analyzed a detailed comparison between traditional highway construction and green highway construction and identified how green highways are important to the improvement of the country's economy. ongoing and upcoming highway construction projects are facing difficulties in completing and carrying out their projects due to the economic crisis. The study has suggested that applying the green highway concept and gaining its potential economic benefits to the Sri Lankan context is an innovative solution to address the economic challenges.

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DEVELOPMENT OF GEOPOLYMER PASTE USING BOTTOM ASH AND POTASSIUM HYDROXIDE AS THE PRIMARY POLYMERIZATION MATERIALS

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Abstract: Geopolymer concrete (GPC) is considered an effective alternative to conventional concrete because of its low embodied energy consumption and positive impacts on the environment. However, the unpopularity of GPC among the construction industries is mainly due to the high cost of production and safety-related issues. This study deals with developing geopolymer paste (GPP) in a more sustainable manner using bottom ash (BA) and granulated blast furnace slag (GBS) as precursors and potassium hydroxide (KOH) incorporated sodium silicate (Na_2SiO_3) based alkaline solution. The overall program is based on three stages: firstly, optimizing BA to GBS ratio among the selected replacement levels of 0%, 20%, 40%, 60%, and 80% by weight (using a fixed alkaline solution concentration of KOH: Na_2SiO_3: Water, 1.0: 1.5: 0.5 by weight); secondly, optimizing the dosage of KOH in alkaline solution among 10M, 12M, 14M, 16M 18M and 20M (using the optimum BA to GBS ratio); finally, optimizing the heat-curing temperature in the selected range of 60°C to 120°C at 20°C increments. These stages are done concerning fresh and hardened state properties such as consistency, initial setting time, and flexural strength, and finally compared with the performance of conventional paste prepared using Ordinary Portland Cement (OPC). Results revealed that consistency of 6 – 8mm, an initial setting time of 450 minutes, and a 7-day flexural strength of 4.8MPa is achievable with GPP containing 100% BA and KOH dosage of 16M cured at 120°C temperature. This is identified as the best proportion among the selected BA to GBS ratios and also more effective than the conventional OPC paste resulting in the same consistency, an initial setting time of 160 minutes, and a 7-day flexural strength of 3.5MPa. Moreover, the inclusion of GBS did not prove the satisfactory performance of GPP compared with the conventional cement paste.

Keywords: Geopolymer Paste; Bottom ash; Heat Curing; Consistency; Setting Time; Flexural strength

1. Introduction

Production and manufacture of Ordinary Portland Cement (OPC) concrete results in high CO_2 emissions to the atmosphere, causing an ecological imbalance and the depletion of natural resources. To mitigate these negative effects on the environment, and because of the finite resources for cement production, new binding materials known as 'geopolymers' for use in the construction industry are preferable. The primary goal of achieving sustainable construction materials is to reduce the use of virgin materials in the production of concrete. To address these issues, geopolymer concrete (GPC) was developed, which can eliminate the OPC cement with by-products and water with an alkaline solution.

Geopolymer concrete has more advantages than other alternative green concrete. This research mainly focuses on investigating the granulated blast furnace slag (GBS) and bottom ash (BA) based geopolymer paste (GPP) and obtaining the performance of BA-based geopolymer by optimizing the influencing parameters of geopolymers. The significance of this study is the utilization of BA for GPC because, in most of cases, fly ash (FA) based GPC has been studied to an extent. BA is also a waste by-product that causes environmental pollution. By successfully incorporating BA in GPC the dumping problems of waste by-products resulting from coal power plants can be reduced and also it is possible to motivate sustainability of the concrete production.

2. Literature Review

The rising demand for coal to generate electricity for the energy industry will increase the amount of coal ash. Generally, ash-burning coal will account for roughly 10% of total coal utilized in a coal-fired power station. This hazardous coal fly ash, estimated to be 10 million tonnes in 2019, will peak in 2050 (Adelizar et al., 2020). BA and FA are the most containing coal ash in coal power plants (Bajare et al., 2013). Thermal waste now become a huge threat to the ecosystem due to open dumping.

Geopolymers are three-dimensional networks of cross-linked $[AlO_4^-]$ and $[SiO_4^-]$ tetrahedral units with alkali metal cations (Jia, et al., 2019). By balancing the negatively charged $[AlO_4^-]$ units, as shown in Figure 2. The strength is obtained by polymerizing -Si-O- and -Al-O- units, which is very comparable to organic polymerization. According to Davidovits et al. (2010). Amorphous or partially crystallized geopolymers are common. There are four main steps behind geopolymerization. Firstly, a chemical attack occurs after that dissolution, gel formation, geopolymerization and finally geopolymer growth occurs with the curing. According to the current studies of GPC, the mix design is a huge challenge compared to the OPC such as changing the concentration of the alkaline activators which has a direct impact on the performances of the geopolymerization reaction and the bonding.

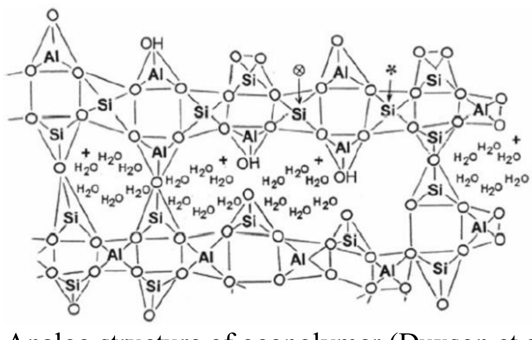

Figure 1: Analog structure of geopolymer (Duxson et al., 2007).

According to the mix design of Rangan, the 'water-to-geopolymer solids ratio' by mass was devised as a single parameter. The total mass of water in this parameter is the sum of the masses of water in the sodium silicate solution, the sodium hydroxide solution, and any extra water added to the mixture. The mass of geopolymer solids is the sum of the masses of fly ash, sodium hydroxide solids, and sodium silicate solids.

Based on the problems associated with current construction activities which are reported and concerning the previous research studies, the following gaps were identified which are used in this study as well as for future directions: development of a NaOH-free binder that is similarly convenient to OPC concrete; development of BA-based geopolymer concrete with the addition of GBS; investigation of ambient temperature curing method to achieve high early strength GPC; detailed calculation of the carbon footprint and the effective production cost comparison with conventional concrete and investigation of the effects of Fiber-reinforced polymer (FRP) strengthened BA-based GPC.

Since FA-based GPC has been already examined to an extent, the use of BA for this purpose is of primary relevance. In addition to being a waste product, BA pollutes the environment. This research is crucial for promoting sustainability in the construction industry and reducing the amount of BA dumping. It is also possible to encourage sustainable concrete production through this research and develop user-friendly, and effective concrete for the sector.

3. Methodology

The overall program is based on three stages: firstly, optimizing BA to GBS ratio among the selected replacement levels of BA by GBS at 0%, 20%, 40%, 60%, and 80% by weight (using a fixed alkaline solution concentration of KOH: Na_2SiO_3:Water, 1.0:1.5:0.5 by weight); secondly, optimizing the dosage of KOH in alkaline solution among 10M, 12M, 14M, 16M 18M and 20M (using the optimum BA to GBS ratio) and finally, optimizing the heat-curing temperature in the selected range of 60ºC to 120ºC at 20ºC increments. These stages were done concerning fresh state properties such as consistency and, initial setting time, as well as hardened state property of flexural strength. The performance of GPCs was finally compared with conventional paste using OPC paste. Figure 2 represents the schematic diagram of the overall methodology of the study.

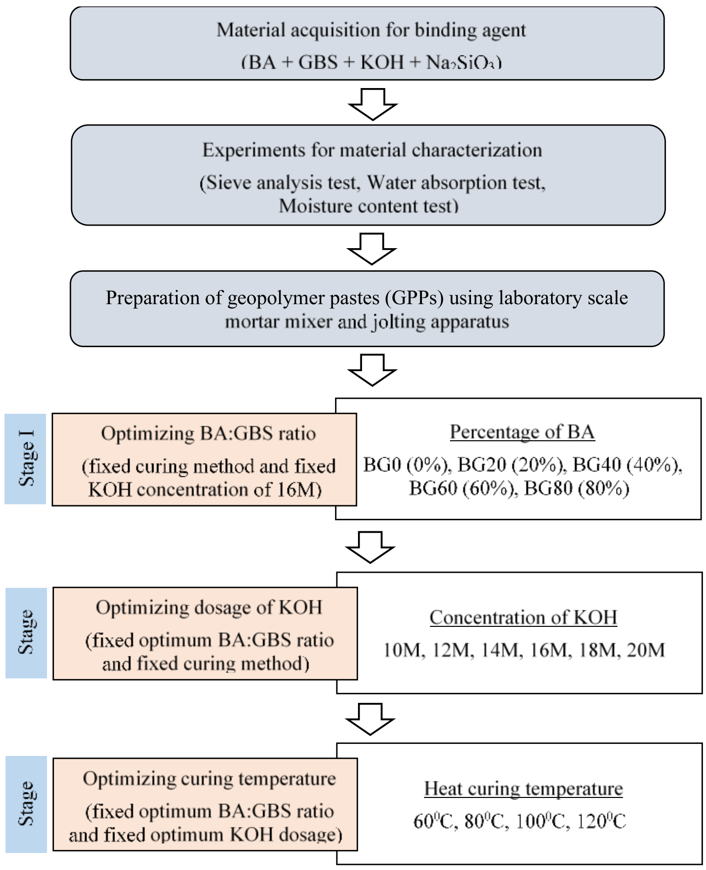

Figure 2: Flow chart of methodology.

3.1 Materials

Materials used in this study include BA obtained from Norochcholai Lak Vijaya coal-fired power plant, GBS supplied by the INSEE Cement (Pvt) Ltd., Sri Lanka, and potassium hydroxide (KOH) and sodium silicate (Na2SiO3) solutions collected from Glorchem Chemical Enterprises (Pvt) Ltd. Figure 3 represents the representative samples of GBS and BA before the preparation of GPP.

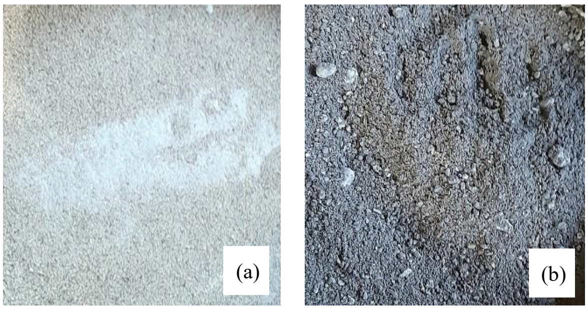

Figure 3: GBS sample (a); BA sample (b).

The experiments for materials include a sieve analysis test by BS 812, allowing evaluation of the BA's particle size distribution. The BA's capacity to absorb water was assessed using the water absorption test concerning ASTM D2216. This evaluation is crucial for comprehending the BA's moisture-related behaviour where the moisture content test was conducted based on ASTM C128. Figure 4 and Figure 5 respectively represent the gradation curves of GBS and BA. The fineness modulus of GBS and BA was identified as 4.954 (0.3mm particles are retained 95.6%) and 4.703 (0.3mm particles are retained 92.5%) respectively. In general, GBS and BA particles are quite coarser which would be an issue for the workability and strength of GPP. Coarser particles may result in a more heterogeneous microstructure, potentially leading to reduced mechanical properties and increased susceptibility to cracking and degradation (Arulmoly et al., 2023).

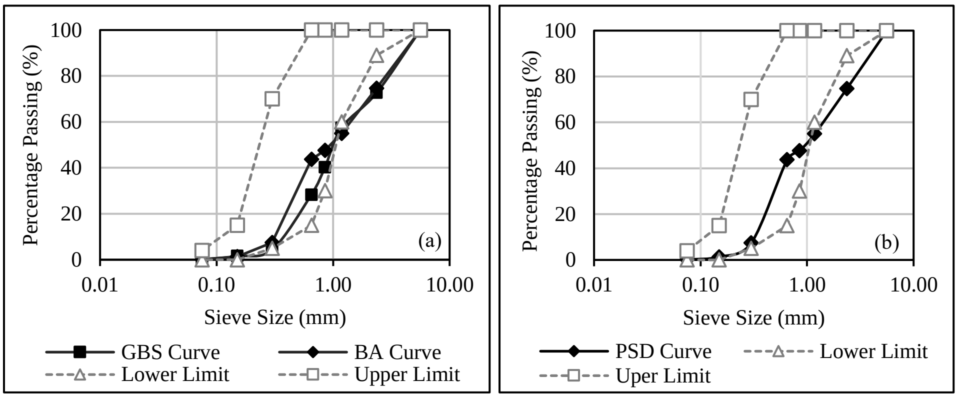

Figure 4: Gradation curves of (a) GBS & BA & (b) blended form.

3.2 Preparation of Geopolymer Paste (GPP)

After the characterization of materials for binding agent, the preparation of GPPs was commenced. This research has three major stages where Table 1 represents the mixing proportions of GPP ingredients for the selected stages of the study as discussed in Figure 2.

Table 1: GPP ingredients at different stages in kg/m^3

Mix Code		KOH	Na_2SiO_3	Water	BA	GBS
Stage I	BG0	135	135	31	1150	0
	BG20	135	135	31	920	230
	BG40	155	155	35	690	460
	BG60	155	155	35	460	690
	BG80	103	103	24	230	920
Stage II	KOH10	124	124	111	1200	0
	KOH12	138	138	83	1200	0
	KOH14	151	151	58	1200	0
	KOH16	162	162	37	1200	0
	KOH18	171	171	18	1200	0
	KOH20	180	180	0.81	1200	0
Stage III	60C	180	180	0.81	1200	0
	80C	180	180	0.81	1200	0
	100C	180	180	0.81	1200	0
	120C	180	180	0.81	1200	0

After weighing the raw materials according to the mix design firstly BA and GBS were mixed using a laboratory mortar mixer. After that, the required amount of Na_2SiO_3 and KOH were separately mixed in a beaker and then added to distilled water. During this mixing exothermic reaction was observed. The solution was then added to the mixer at one time and thoroughly mixed to obtain a homogeneous paste. As shown in Figure 6, the paste then was molded in 3-gang mortar prism molds (40mm × 40mm × 160mm) and compacted using jolting apparatus at two (2) sets consisting of 30 blows. This frequency and vibration were maintained for each GPP.

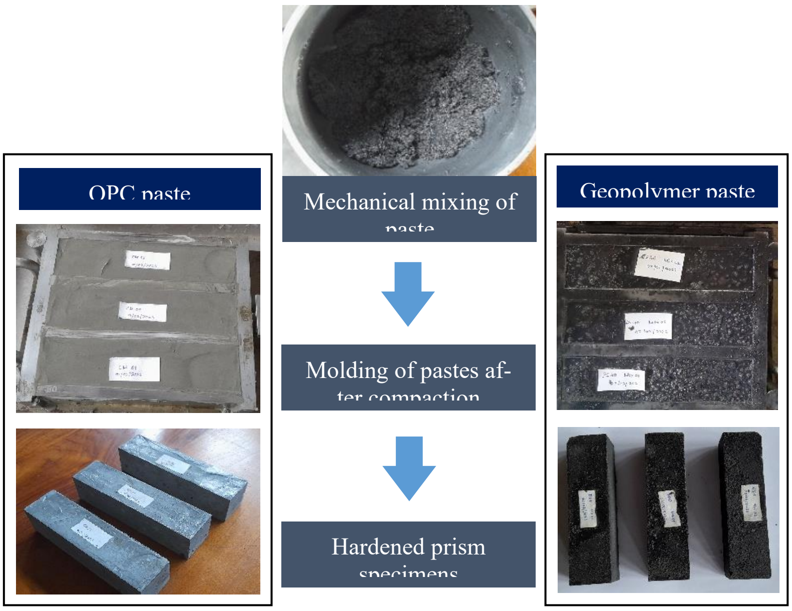

Figure 5: Preparation of fresh paste and hardened specimens.

After preparing the fresh paste specimens, they were kept undisturbed until 450 minutes which was the average initial setting time for the GPPs. After that GPP prism specimens were demoulded and heat-cured continuously for 24 hours while OPC prism specimens were pond-cured until the test day.

3.3 Experiments

Tests for pastes were done at two stages: during the fresh state and the hardened state. For the fresh pastes, initially consistency test was carried out using the Vicat test apparatus as per ASTM C191. This was done to investigate the flow and viscosity of fresh pastes. Once the consistency test was done, based on the water requirement the initial setting time test was done according to the same standard. Figure 7 represents the consistency and initial setting time test setups with a typical fresh GPP.

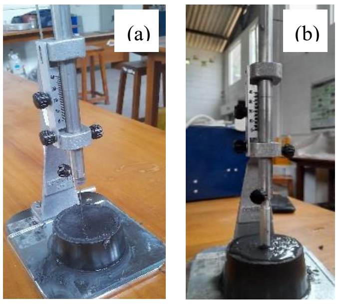

Figure 7: Consistency test setup (a); initial setting time setup (b).

Regarding the hardened paste investigation, firstly the unit weight of pastes was determined after the required curing and exposure at an elevated temperature of 100±5ºC according to ASTM C138 standard. Another set of specimens underwent for flexural strength test using a compression testing machine according to ASTM C78 standard. The prism specimens were subjected to three-point loading at a standard loading rate and forced to split along the mid-span.

4. Results and Discussion

4.1 Initial setting time

Figure 8(a) represents the initial setting time of GPPs used for Stage I. The addition of GBS increased the initial setting time of pastes. This could be related to several aspects such as the dilution effect. The addition of GBS increases the solid content and thus reduces the concentration of activators. The addition of GBS also alters the chemical composition of GPP. GBS contains compounds like calcium oxide (CaO) and calcium sulfide (CaS), which can react with the alkali activators and water present in the paste. These reactions can consume some of the activators, resulting in reduced availability for the polymerization process.

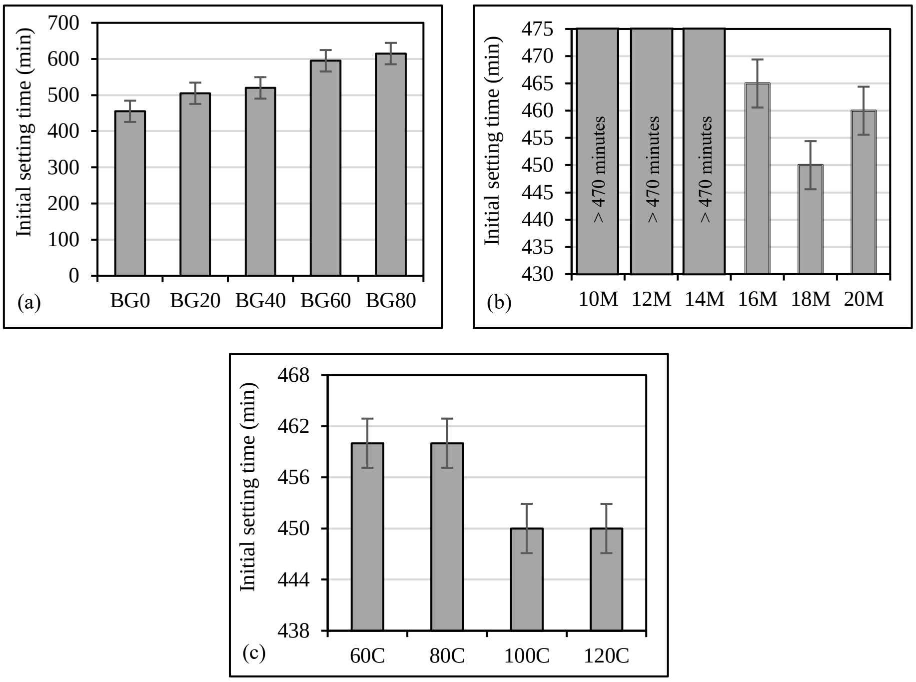

Figure 6: Average initial setting time of pastes: (a) Stage I; (b) Stage II; (c) Stage III.

As per Figure 8(b), when the concentration of potassium hydroxide (KOH) was increased in the 100% BA-based GPP, it could have a significant impact on the initial setting time. The relationship between KOH concentration and setting time typically follows abnormal behavior, where initially increasing concentration reduced the setting time, but beyond a certain point, further increase in the concentration advanced the setting time. The possible reasons could be due to the water demand, activation effect, and optimal alkalinity.

Increasing the curing temperature reduced the initial setting time (refer to Figure 8(c)) which could be because of the acceleration of chemical reaction and leads to faster formation of geopolymer gels. Increasing temperature could also enhance the mobility and diffusion of ions and molecules within GPP. Curing temperature may also affect the water evaporation which may reduce the liquid content and promote the formation of a solid network and thus accelerate the setting time. The GPP's flow and workability were restricted by its consistency of 6–8 mm throughout the study.

4.2 Unit weight

Figure 9(a) shows the average unit weight of pastes where a slight increase in unit weight could be observed after curing GPPs with an increased sequence of GBS. The increased solid content, enhanced particle packing, and increased density of reaction product could be possible solutions for this variation. Moreover, the results directly depend on the specific gravity of BA and GBS. According to Figure 9(b), the unit weight was increased concerning the increment of KOH concentration in BG0 (GPP contained 100% BA). This was attributed to several factors, such as increased solid content-enhanced geopolymerization, and improved packing density.

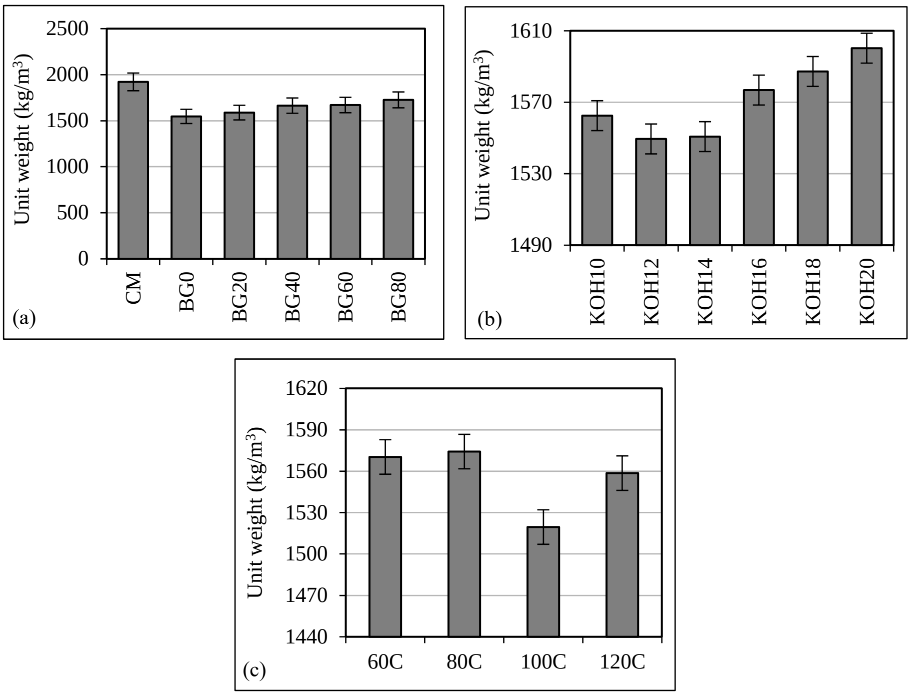

Figure 9: Average unit weight of pastes: (a) Stage I; (b) Stage II; (c) Stage III.

As per Figure 9(c), based on the results heating the geopolymer material could cause thermal expansion and rapid evaporation of free water. These thermal effects may lead to slight changes in the unit weight of pastes. However, these are generally minimal effects while the changes in results could mainly depend on the specific composition of the geopolymer.

4.3 Flexural strength

Figure 10(a) refers to the flexural test results of GPPs prepared at Stage I. The average strength of revealed the highest flexural strength of around 3.5MPa among the other replacement levels. Increasing GBS content reduced the flexural strength which could be a variation of the particle characteristics of GBS. In general, ground granulated blast furnace slag (GGBS) has fine particles similar to the GBS particles. Therefore, increased particle smoothness could reduce the particle interlocking and thus the frictional effect between the particles of GPP. This may decline the strength of GPP. Moreover, GBS typically has a lower reactivity compared to other geopolymer precursors like BA. Therefore, increasing GBS content could dilute the more reactive components, which can result in a less effective polymerization process.

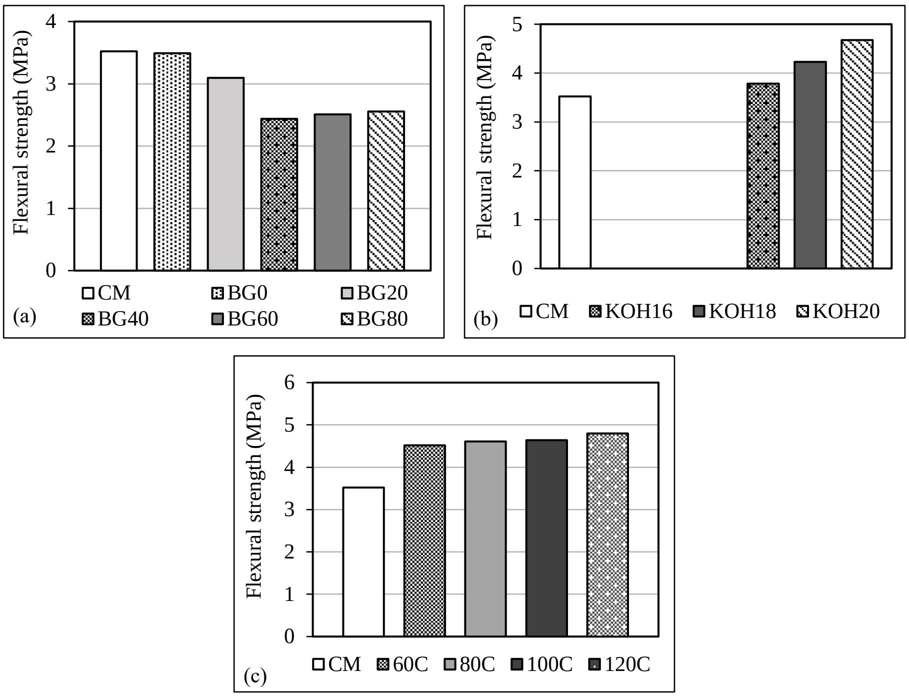

Figure 10: Average flexural strength of pastes: (a) Stage I; (b) Stage II; (c) Stage III.

The flexural strength of GPPs used for Stage II is represented by Figure 10(b). Overall, KOH20 GPP arrived with the highest flexural strength of around 4.8MPa among the selected KOH concentration levels. Increment of KOH concentration led to accelerated chemical reaction and enhanced formation of geopolymeric gel. This gel is the main factor that could improve the strength and stability of GPP. Figure 10(b) only refers to the flexural strength of KOH16, KOH18, and KOH20 GPPs because KOH10, KOH12, and KOH14 GPPs took too much time to set in. Due to this the initial setting time and flexural test results were unable to be determined. It was identified that the selected low KOH concentration was not enough to achieve the required polymerization to create GPPs.

Figure 10(c) shows the flexural test results of the Stage III GPPs. In this stage, two influencing parameters were optimized which are BG0 (100% BA-based GPP) and KOH20 (KOH concentration of 20M) by maintaining those conditions. The change in curing temperature significantly influenced the strength of GPPs where at higher curing temperature higher flexural strengths were noticed (A curing temperature of 120^{o}C resulted in the highest flexural strength of around 4.8MPa).

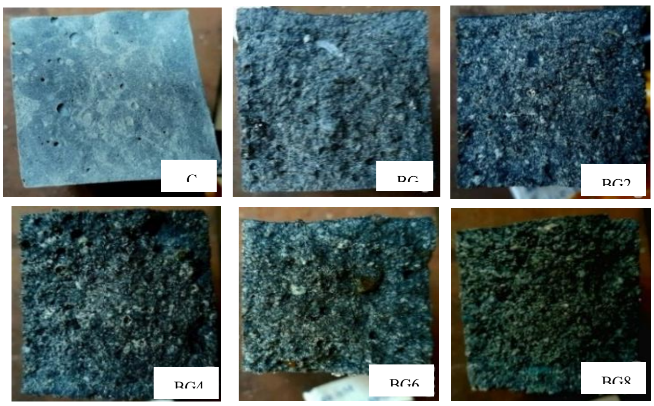

Figure 11: Pores development in CM and GPPs (Stage I).

Figure 11 shows the cross-section of Stage I GPPs which could be used for observation of porosity of GPPs and how it affects the strength development as a detailed future study. From BG0 to BG80, the internal surface texture and porosity are gradually increased. Due to the zero addition of small-sized particles of GBS, the flexural strength of BG0 was the highest among the selected replacement levels. The possible reasons for the strength development in GPPs mainly involve three parameters: particle sizes of raw materials (coarse particles have a slow rate of reaction with the alkaline solution); KOH concentration (when the concentration of KOH increased, gel formation process is effective and reaction with the binders will speed up the rate of polymerization and create strengthen bonds); curing temperature (heat curing is the most convenient curing and when the curing temperature is increased the polymerization is advanced). Focusing on those parameters also forces us to consider the production cost of the GPPs which requires a detailed future study.

5. Conclusion

This study investigates the effects of including GBS, varying KOH concentration, and the addition of Na_2SiO_3 on the performance of BA-based GPPs.

- Changing KOH concentration did not significantly improve GPP's performance and no effective results were obtained for GPPs including GBS.
- The initial setting time was gradually increased with the increment of GBS in GPPs while an abnormal trend was observed with KOH concentration. However, higher curing temperatures quickly allowed the GPPs to set due to the increased rate of reaction. Unit weight is not a critical parameter in this study. However, each BA-based GPP revealed reduced unit weight compared to CM due to the low specific gravity of BA and GBS.
- Regarding the flexural strength results, an optimized performance could be achieved with GPP containing zero GBS which revealed almost similar strength to CM. The results of Stage II and Stage III manifest that each selected KOH concentration level and curing temperature advanced the strength of BA-based GPP than CM. Concerning the economic GPP production, it is suggested to use GPP containing 100% BA with an alkaline solution containing a KOH dosage of 16M, heat cured at 60ºC. This mix design is effective for increasing the strength of GPP by around 42% more than CM.

To thoroughly evaluate this geopolymer system's appropriateness for its intended use, more research should be done to examine its long-term durability, cost-effectiveness, and scalability.

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DURABILITY OF ORDINARY CONCRETE MADE OF MANUFACTURED SAND AND OFFSHORE SAND

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Abstract: Demand for river sand has escalated nowadays. This creates a question on utilizing conventional fine aggregates and thus an increased usage of alternatives for concrete. Manufactured sand and offshore sand have been incorporated as the primary replacements for river sand by a few industries. In the present study, river sand was completely replaced by manufactured sand alone, offshore sand alone, and blending of manufactured sand and offshore sand at 25%, 50%, and 75% replacement levels (by weight) in ordinary concrete to check the durability characteristics such as water absorption, sorptivity, weight, and compressive strength losses in 10% sulfuric acid environment. Results revealed that the lowest water absorption was identified in concrete containing 50% manufactured sand and 50% offshore sand after 24 hours of complete immersion in water while the optimum resistance against sorptivity at 7 days was identified in concrete made of 25% manufactured sand and 75% offshore sand. Performance against the acidic environment was optimum in concretes made of 100% offshore sand and other blending mixtures. Overall, the mixtures of all fine aggregate types except MS alone manifested better durability properties compared to RS concrete. Therefore, all selected blended fine aggregates could be applied by completely replacing RS in concrete.

Keywords: Ordinary Concrete; River sand; Manufactured sand; Offshore sand; Durability

1. Introduction

Concrete is the most widely used man-made construction material in the world. It is a composite material consisting of cement, coarse aggregate, fine aggregate, water, and admixtures (when required). Fine aggregates are the particles lesser than 4.75mm sieve and greater than 0.075mm. The main role of fine aggregate in concrete is that it acts as a filling material, reducing the amount of cement required. Fine aggregates have some percentage of micro-fines that lead to a reduction in segregation in concrete (Arulmoly et al., 2022).

Most contractors still use river sand (RS) as the primary fine aggregate because of the high workability, strength, and durability of cement-based mixtures (Sing et al., 2012, Arulmoly and Konthesingha, 2021). The demand for river sand has escalated nowadays due to the restrictions on riverbed extraction and to overcome rapid infrastructure developments. This creates questions on utilizing conventional fine aggregates and, thus an increased usage of alternatives for concrete. A considerable number of studies reveal that sea sand, offshore sand (OS), quarry dust, manufactured sand (MS), waste glass, and plastic wastes, are some of the alternatives that can replace RS in terms of strength and fresh state properties (Arulmoly et al., 2021, Ashwin, 2015, Aswath, M., 2014).

Although MS and OS have been incorporated as the primary replacements for RS by a few industries, most contractors are reluctant to use these alternatives due to less satisfaction with their long-term performance in concrete. Therefore, the present research focuses on investigating the effects on the durability of normal concrete made of MS, OS, and a combination of them.

2. Literature review

Based on a previous study, the demand for sand for building construction in Sri Lanka was identified as 7-7.5 million cubic meters per year (Piyadasa, 2011), which accounts for nearly 40% of extraction from Western Sri Lanka and 60% of the rest of the country (Pereira et al., 2013). This leads to uncontrolled river sand mining which causes serious environmental problems like riverbank erosion, riverbed degradation, and loss of vegetation on the bank of rivers, etc. (Sankh et al., 2014). MS is one of the best alternatives for RS, which is free from organic impurities as they are manufactured from parent rocks (Rathore, et al., 2018; Arulmoly et al., 2022). The unique properties of MS, such as dense particle packing, slit-free nature, angular and rougher surface, and absence of organic impurities, lead to various positive impacts on fresh and hardened characteristics of concrete like high strength, improved abrasion, low permeability, and less dry shrinkage (Elavenil et al., 2013, Rathore, et al., 2018, Tharshigan et al., 2019).

OS has also become a better RS alternative which is extracted from deep-sea beds. The study made by Dias et al. (Dias et al., 2008) proved that offshore sand extracted from the Western coast of Sri Lanka with reduced chloride content satisfied the performance of concrete against corrosion. The author identified that 0.075% chloride content is safe for OPC-reinforced concrete. The research work done by Arulmoly et al. (Arulmoly et al., 2021) proved that the void content of MS was relatively higher than RS in its natural form. However, the porosity of MS was reduced to an extent by blending with round and tiny offshore sand particles, which could be considered as a base for the present study.

The durability of concrete is essential which is the ability to resist weathering action, chemical attacks, or any deterioration. Durability depends on various factors, including chloride and sulfate diffusion, carbonation behavior, freeze–thaw resistance, and drying shrinkage (Xiao et al., 2017). The different natures of alternative fine aggregates may significantly influence the long-term performance of concrete. For instance, the shape and gradation of fine aggregates impact the permeability of concrete, lower absorption of fine aggregates reduces freeze-thaw resistance, properly graded fine aggregates minimize cracks, and high quality of fine aggregates prevent undesirable chemical reactions. However, the literature is lagging on these concepts and the influence of sand particle characteristics which should be addressed properly.

3. Methodology

3.1 Materials

Materials used in this study are blended cement, RS, MS, and OS as fine aggregates, and crushed granite stones as the coarse aggregate. RS was collected from a riverbed located in Southern Sri Lanka where MS and OS were extracted from Western Sri Lanka. Initially, materials were undergone for particle size distribution test where Figure 1 shows the gradation curves of the selected fine aggregates. As can be observed, the distribution curve of OS and RS satisfied the upper and lower limits according to BS 812-1 (British Standard, 2002). However, MS manifested some abnormal behavior for some size ranges. Table 1 shows the water absorption and specific gravity values of selected fine aggregates resulting from standard experiments.

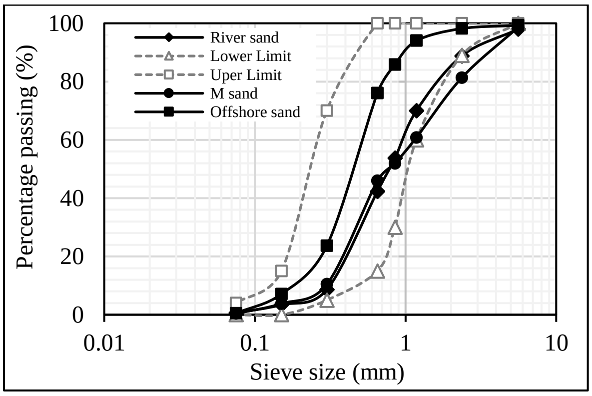

Figure 1: Particle size distribution.

Table 1: Water absorption and specific gravity

Experiment (Standard)	RS	MS	OS
Water absorption (%) (ASTM C128)	2.00	4.06	2.15
Specific gravity (ASTM C128)	2.68	2.77	2.65

3.2 Mix design

Concrete mixtures with grade C30 were prepared throughout the study. RS concrete was used as the control mix while the alternative concrete mixtures were prepared by replacing MS by OS at 0%, 25%, 50%, 75%, and 100% (by weight). A total of six (6) different blending ratios were selected. The British method (DoE) was adopted for designing the concrete and for each mixture the water-to-cement ratio (w/c) was kept constant at 0.54 to avoid the influence of free water on concrete properties. Table 2 shows the mix proportions of concrete mixtures. A machine mixing method was adopted to prepare concretes maintaining a room temperature of 36±2ºC.

Table 2: Proportion of concrete ingredients (per m^3 of mix)

Materials		Mixing proportions					
		RS	MS	OS	BS1	BS2	BS3
Cement		380	380	380	380	380	380
FA	RS	605	-	-	-	-	-
	MS	-	620.5	-	464.1	306.85	153.43
	OS	-	-	610.3	154.7	306.85	460.28
CA		1175	1204.5	1184.7	1201.2	1191.3	1191.3

Water	205	205	205	205	205	205
RS: Concrete with 100% RS MS: Concrete with 100% MS OS: Concrete with 100% OS BS1: Concrete with 75% MS + 25% OS BS2: Concrete with 50% MS + 50% OS BS3: Concrete with 25% MS + 75% OS FA: Fine aggregate CA: Coarse aggregate						

3.3 Experiments for Fresh and Hardened Concrete

3.3.1 Workability test

The slump test was conducted to determine the workability or consistency of fresh concrete according to ASTM C143 (ASTM International, 2010). After mixing of concrete, fresh concrete was filled into three layers by tamping each layer by tamping the rod at 25 times. Any excess concrete was then removed and the surface of the cone was leveled with the top edge of the cone.

3.3.2 Compressive strength test

The compressive strength was determined using cube specimens having dimensions of 150mm × 150mm × 150mm using ASTM C39 (ASTM International, 2014). After mixing and molding, concrete cubes were allowed to be set for 24 hours without any external vibrations, followed by the demolding process. After that specimens were pond-cured for 28 days and then tested for their compressive strength using a Universal Testing Machine (UTM) with a compression capacity of 3000kN.

3.3.3 Sorptivity test

The sorptivity test was carried out according to ASTM 1585 (ASTM International, 2013). Two (2) cylindrical specimens having 100mm diameter and 50mm thickness were cast for each mixture. After seven (07) days of pond curing, the samples were placed in an oven maintained at 50℃ for 3 days. After that, each specimen was placed inside a separate sealable container for 15 days. Then, the specimens were removed, and the mass and diameter of each specimen were recorded. Here, the water level was maintained at 1mm to 3mm above the top of the support device. The mass of the surface dried sample was measured at 1, 5, 10, 20, 30, and 60 min and was continued for every hour up to 6 hours. The final measurement was taken 24 hours after the measurement at 7 days. Figure 2 shows the procedure of the sorptivity test and Equation (1) was used to determine the absorption rate (I).

$$I = m_t / (a \times d) \qquad (1)$$

where,

m_t - change in specimen mass in g; a - exposed area of specimen in mm^2

d - density of water

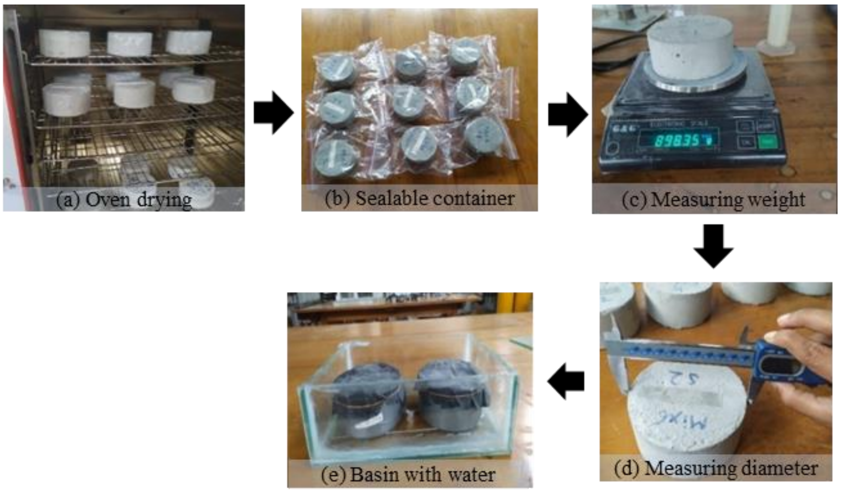

Figure 2: Procedure of sorptivity test.

3.3.4 Water absorption test

The water absorption test was conducted based on the oven drying method according to ASTM C642 (ASTM International, 2003). Concrete cube specimens were fully submerged in water for 28 days, which was followed by taking saturated surface dry (SSD) weight measurements. Concrete specimens were then oven-dried at 110°C for not less than 24 hours. Then, they were allowed to cool in dry air to reach the room temperature. The specimens' water absorption (W) was determined as provided in Equation (2).

$$W\ (\%) = (B - A) / A \tag{2}$$

where,
A - dry weight of specimen; B - saturated surface dry (SSD) weight of specimen

3.3.5 Acid resistance test

The acid resistance test was conducted for 150mm × 150mm × 150mm concrete cubes. The percentage loss of weight and compressive strength test were checked after 56 days. Initially, the dry mass of specimens was measured and then they were immersed in a water-diluted 10% sulfuric acid (H_2SO_4) solution. During this experiment, it was ensured that no direct contact/evaporation of acid solution to the environment and the changes in the appearance of concrete cubes were frequently monitored.

4. Results and Discussion

4.1 Workability

Figure 3 shows the test results obtained from the slump test. It can be identified that concrete containing the selected sand types of RS, MS, and OS alone came up with a slump in the range of nearly 90 – 100mm. However, this property was slightly increased for concrete made of blended sand types. The maximum workability of 135mm was noticed in the concrete with 75% MS and 25% OS and this was gradually reduced with increasing replacing levels. The rationale for this behavior could be due to the combined lubricating effect of the ultra-fines of MS and more rounded OS particles in between the coarse particles in the mix. This lubricating effect could advance the viscosity effects in concrete. Hence, it can be said that the selected blending levels of MS and OS are effective for producing higher workable concretes than RS concrete.

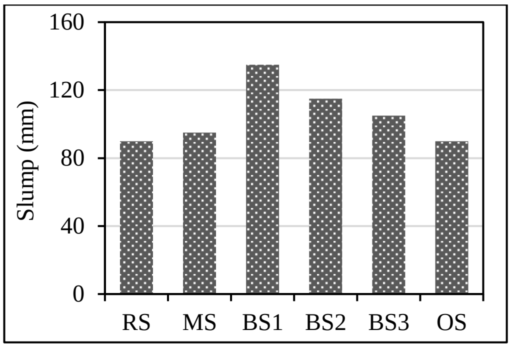

Figure 3: Workability of concrete mixtures.

4.2 Compressive strength

The results of the compression strength test of concrete are represented in Figure 4. This behavior is in contrast to the workability, where concrete with RS, MS, and OS alone manifested higher compression strength than concrete with blended sands. Overall, the MS concrete showed the highest strength of nearly 40MPa at 28 days of curing which was due to high particle interlocking behavior with the assistance of angular edges and the rough texture of MS particles. Considering concrete specimens with a higher percentage of OS, the 28-day - compressive strength was lowered due to smooth and round particles. However, the optimum strength of nearly 30MPa was achieved by concrete containing 50% MS and 50% OS.

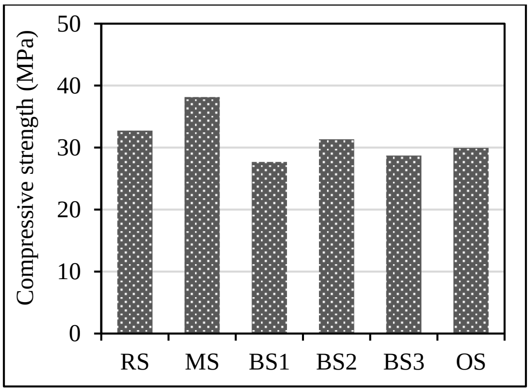

Figure 4: Compressive strength of concrete mixtures.

4.3 Sorptivity

The sorptivity was measured concerning time and the outcomes of the experiment are provided in Figure 5. It can be clearly understood that the sorptivity of RS concrete was very low as RS naturally has low porosity and good particle packing, which could restrict the flow of water through the concrete. The combination of well-graded particles and their interlocking nature in RS could contribute to a reduction of water absorption and sorptivity. Regarding the concrete made with blended sand types, the sorptivity of the BS1 mixture was very high. This could be because the presence of MS, which typically has a more angular and rougher particle shape, may lead to increased voids and reduced particle packing, allowing more water to penetrate the concrete and resulting in higher sorptivity values.

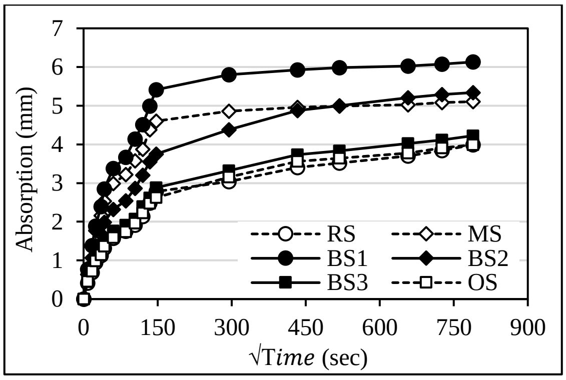

Figure 5: Sorptivity of concrete mixtures.

BS3 and OS concretes revealed low sorptivity due to the higher presence of OS. This leads to a reduction of the surface area available for water absorption and thus minimizes water infiltration. The higher proportion of OS further contributes to a denser concrete matrix, reducing the permeability and water absorption capacities.

4.4 Water absorption

Figure 6 depicts the water absorption capacities of concretes made of the defined fine aggregate types. All in all, OS had the highest water absorption due to the presence of finer particles and potentially higher porosity. The finer particles and increased porosity provide more pathways for water to be absorbed into the concrete, resulting in higher water absorption. RS manifested the lowest water absorption because of the particle size distribution and particle shape which contribute to its lower water absorption. Among the blended sand types, the BS2 mixture revealed the smallest water absorption rate compared to other blended mixes.

MS, with its angular and rough particle shape, tends to have higher water absorption due to the creation of micropores in concrete once hardened. However, when blended with OS, this porosity could be reduced to an extent that helps to reduce the overall water absorption rate.

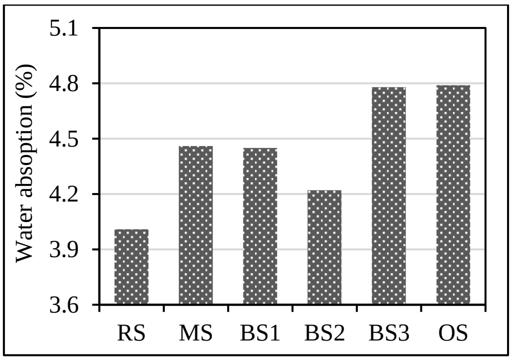

Figure 6: Water absorption of concrete mixtures.

4.5 Acid resistance test

In this study, the resistance of concrete specimens against an acid-based environment was checked using the losses in weight and compressive strength after considerable acid-curing. Concerning Figure 7, concrete contained 75% MS and 25% OS came up with the lowest weight loss of around 11.5%. However, an abnormal trend can be noticed between other blending levels, hence a solid conclusion cannot be achieved at this stage. A significant loss in weight can be observed for RS and MS concretes compared with the other concrete mixtures.

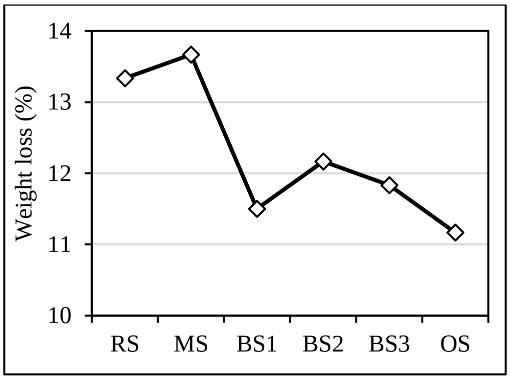

Figure 7: Weight loss after acid attack.

Overall, the concrete mixtures containing RS and OS alone came up with an outstanding performance against the H_2SO_4-acidic environment, which revealed a compressive strength loss of nearly 2.5% concerning Figure 8. On the other hand, MS concrete showed the highest loss of around 20%, which is not a positive aspect. This could be due to the changes in the cement chemistry and the interfacial transitional zone (ITZ) as a result of chemical reactions between the composition of parent rocks and acid. These results require a detailed study in the future on this concept.

In terms of concrete made with blended fine aggregates, a small strength loss can be identified, and the proposed blended ratios of MS and OS can be proposed for durable concrete to resist extreme conditions. There are limitations as only one acidic environment is considered, but a comprehensive study is required to achieve a solid conclusion.

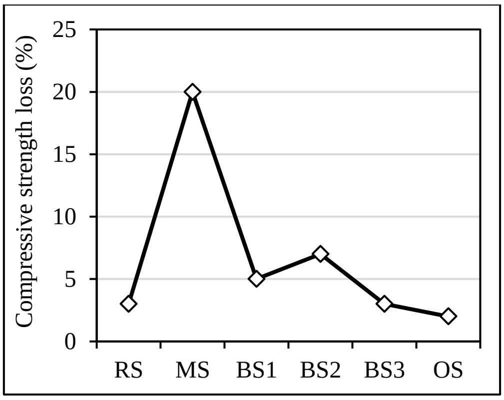

Figure 8: Compressive strength loss after acid attack.

Figure 9 represents two MS concrete specimens after an acid attack for 56 days. As shown, the specimens were undergone for severe acid attack which is clear from the significant color changes. However, internal changes in specimens cannot be observed or predicted here which could be a main rationale for compressive strength reduction. By analyzing scanning electron microscopy (SEM) it is possible to arrive at a solid conclusion.

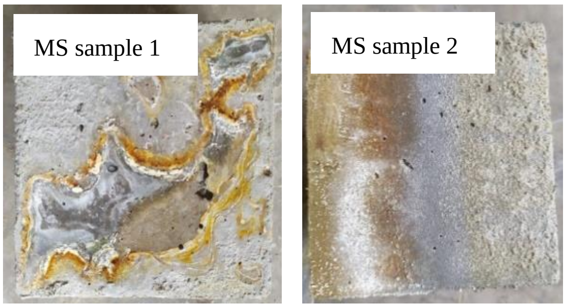

Figure 9: MS concrete specimens after acid attack.

5. Conclusion

This study deals with investigating the pertinence of RS alternatives such as MS, OS, and blending of both for improving the durability characteristics of concrete. Results revealed that BS2 concrete had the lowest water absorption, while the optimum resistance against sorptivity was observed in concrete made of BS3 and OS alone. Performance against the selected acidic environment was maximum in concrete made of BS1 and OS by considering the weight loss, and the best performance came up in concrete made of OS in terms of compressive strength loss. A small loss in compressive strength can be identified in concretes containing BS1, BS2, and BS3 fine aggregates, which can also be proposed for durable concrete to resist extreme conditions.

Overall, the mixtures of all fine aggregate types except MS alone manifested better durability properties compared to RS concrete. Therefore, all the selected blended fine aggregates could be applied by fully replacing RS in concrete.

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MITIGATING URBAN HEAT ISLAND USING COOL PAVEMENT STRATEGY: A CASE STUDY IN COLOMBO, SRI LANKA

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Abstract: Continuous man-made changes in an urban area have led to the phenomenon called Urban Heat Island (UHI). UHI is an adverse condition of increasing urban temperature than its surrounding rural areas. Due to UHI, the thermal comfort of people has been affected badly and many negative impacts have occurred in society. The present research is focused on Cool Pavement as a mitigation strategy for UHI. Reflective concrete pavement was designed using waste glass, ground granular blast Furnace Slag, and white cement. Seven mix designs were created, and strength and temperature graining tests were performed to identify the optimum ratio of material proportions. The results revealed that 10% replacement of slag and 10% replacement of white cement with OPC is the best ratio for the cool pavement, exhibiting superior solar reflection properties in comparison to conventional concrete. The Albedo of this invented CP was measured using the solar radiation sensor of a watchdog weather station. It was found to be 0.455 which highlights the reflective properties. Microclimate in the Fathima church area in Colombo, Sri Lanka has been analyzed in the current study. It is located in a highly metropolitan area which usually has high relative humidity and temperature. Field meteorological data were collected on the 1st of April 2023 using prepared electronic instruments. Invented pavement kept in the study area and compared with an existing concrete pavement. It was found that the invented cool pavement has a 1.4 K lesser surface temperature than conventional pavement. Further, this study explains the concept of UHI and different types of CP strategies.

Keywords: Urban heat island; Cool pavements; Reflective concrete pavement; Albedo

1. Introduction

The global population has increased rapidly, which makes more people move into the urban areas and urban sprawl has been created. This results in various transformations within urban cities including the removal of vegetation covers, high-density residences, conversion of natural soil into artificial pavements, high releasement of anthropogenic heat, etc. These alterations have affected the heat balance of urban areas consequently urban heat islands (UHI) have formed. UHI is a current global problem which is the rise of urban temperature in its surrounding rural areas. This temperature difference can be between 2oC to 4oC (Freire, et al., 2021). Further UHI effect can change in both time and space within the city (Gaffin, et al., 2008). Usually, the UHI effect is higher in the nighttime than in the daytime. UHI effect is increasing with the population growth of a city (Oke, 1973). The most common factors associated with UHI are vegetation cover, season, impervious surfaces, and population density (Phelan, et al., 2015).

The elevated temperature of UHI directly influences the energy demand, air quality, and public health. Cooling energy consumption is double due to the UHI effect (Santamouris, et al., 2001). This escalates greenhouse gas emissions and consequently, global warming occurs. UHI-related poor air quality makes respiratory problems and other health issues worse. Many of these effects fall on vulnerable groups including low-income communities and elderly people. UHI reduces the thermal comfort of people. Additionally, the UHI effect disturbs ecosystems, disrupting biodiversity and changing the behavior of plants and animals. To reduce these adverse conditions, urban planners and researchers have found many mitigation steps like cool materials, green roofs, open spaces, etc. Among those cool materials take prominent option as these materials can easily apply to new structures as well as existing structures. Material presenting high reflection to solar radiation together with a high emissivity factor is known as cool materials (Santamouris, et al., 2001).

Current research is focused on improving microclimate using cool pavement technology. It has been found using cool pavements (CPs) ambient temperature can be reduced up to 3.0K (Battista & Pastore, 2017). Cool pavements can be categorized into three prominent types according to their cooling mechanism. These are reflective pavements, evaporative pavements, and heat-harnessing pavements. Reflective pavements are manufactured with high albedo value therefore those pavements can reflect a higher proportion of solar radiation which results in a reduction of sensible heat releasement into the atmosphere. Consequently, this reduces ambient temperature and the UHI effect. Reflective pavements can be made using light color materials, and by painting with a light color coat or infrared reflective paint. Further reflective color pigments can be incorporated into the pavement structure. In evaporative pavements, cooling is done by evaporation of rainwater. Advanced techniques like heat harvesting, high conductivity materials, and phase change material (PCM) are used to make heat-harnessing pavements. Apart from UHI reduction, numerous benefits from CP interest many researchers. Such as increasing the thermal comfort of people, extending pavement lifespan due to decreased thermal stress, increasing night-time visibility, reducing energy usage, and further increasing potential air quality due to less releasement of certain pollutants, etc.

Many studies have been conducted regarding CP within the past two decades. Santamouris et al., (2001) made a reflective pavement of 0.6 albedo using infrared reflective pigments and found out ambient temperature and surface temperature can be reduced up to 1.9 K and 12 K respectively. By using a modeling approach asphalt pavement changed into 0.4 and 0.6 albedo and ambient temperature reduction was 2.0 K and 3.0 K respectively (Battista & Pastore, 2017). Kolokotsa, et al., 2018 made a CP with albedo of 0.69 and emissivity 0f 0.9. This study only got a 0.3 K ambient temperature reduction. Sen et al., (2019) researched cool materials on roofs, pavements, and walls and analyzed five scenarios. When old asphalt roads change with new ones, the surface temperature of the pavement has increased. This is due to asphalt pavements albedo increase with time. When asphalt was replaced with concrete pavement there was not much change in ambient temperature, while 0.2 K to 0.4 K change occurred in reflective concrete pavement replacement. In 4th scenario, all the roofs and walls were made reflective and 0.4-0.7 K ambient temperature change occurred. When all the pavements, roofs, and walls made reflective, the highest chance of 0.8-1.0 K ambient change occurred. Faragallah & Ragheb (2022) did research in Alexandria to analyze different types of pavement and road materials including colored asphalt roads, brick stones paving, grey color interlock paving, basalt roads, color concrete paving, and granite paving in urban climates. This research concludes among those materials basalt and granite have the best reflection properties. From these studies, it is established that the reduction of the UHI effect depends on local land use patterns, construction materials, climate factors, etc.

To increase the albedo of reflective pavements many materials have been tested. By replacing 20% of fine aggregate with fiberglass, a 4.6 K reduction of surface temperature has occurred in M20 grade concrete pavement (Bhagat, et al., 2012). Boriboonsomsin & Reza (2007) made different concrete mixes by partially replacing cement with slag, fly ash, white sand, and latex. From this study, it is found that 70% replacement of slag gives the best results in the reduction of surface temperature. The Albedo of that mix was 71% higher than the normal concrete mix. This concrete mix consumes 43.5% less energy and results in 20%-60% less emission of pollutants and greenhouse gasses. Further, this study indicates that the inclusion of fly ash reduces the albedo of concrete, making it unsuitable for use in CP construction. There are few studies conducted on waste glass as a reflective pavement material. In grade C30/37 concrete, 20% glass replacement with total aggregates and 30% zeolite replacement with cement got the best reflective properties. The reduction of surface temperature was 12.0 K in this pavement (Pancar, 2016). In M40 grade concrete, 10% replacement of glass with fine aggregate and 10% replacement of zeolite with OPC pavement got 7.9 K surface temperature reduction (Balan, et al., 2021). This concludes optimum proportion of replacement is changed with the grade of the concrete. When glass is used in concrete, silica in glass and alkali in concrete can react and a swell crack can occur. To avoid this Alkali-silica reaction (ASR), zeolite was used in both researches. From the accelerated motor bar test, it was observed that cubes without the inclusion of zeolite did not exhibit an alkali-silica reaction (ASR). This outcome can be attributed to the use of finely crushed glass with a particle size of 1mm. In every research, they have investigated the cooling effect of individual materials, such as the cooling effect of crushed glass, and the cooling effect of slag. The cooling effect of two materials or more together is not investigated. This was identified as a research gap and cool pavement was made using ground granular blast furnace (GGBF) slag, waste glass, and white cement together with other concrete aggregates. Due to chemical reactions in cement manufacturing, a large amount of CO2 is released into the atmosphere. In this pavement design slag is used as a partial replacement for OPC. Therefore, this reduces CO2 emission and consequently increases the potential air quality.

2. Material and method

By considering the merits and demerits of each type of pavement and by analyzing suitability to the current study area, decided to make reflective concrete pavement. To increase the albedo of pavement, ground granular blast furnace slag (GGBFS), waste glass that crushed less than 1mm, and white cement were used. The waste glass was crushed less than 1mm to reduce the alkali-silica reaction.

Seven mix designs were created by replacing different proportions of materials. Glass was replaced with fine aggregate while slag and white cement were replaced by Ordinary Portland cement (OPC). The strength of seven mixed designs was determined after 28 days and Cubes that passed the design strength of 25Nmm-2 were taken into temperature graining analysis. These cubes are kept outside in direct sunlight and analyzed the surface temperature. This surface temperature value is directly related to the reflection ability of pavement. Cube which grained the minimum temperature was chosen as the optimum proportion of aggregates for the CP. Albedo of CP was measured using the solar radiation sensor of the Watchdog Weather Station 2000 series. Table 1 shows the proportions of white cement and slag replacements with OPC while waste glass replacement with fine aggregates.

Table 1: Proportions of slag and white cement replacement with OPC and Waste glass replacement with fine aggregates in each mix design of CP determination

Mix design no	Mix Description	OPC (%)	White Cement (%)	Slag (%)	Sand (%)	Waste Glass (%)	Coarse aggregates (%)
1	Basic mix	100	0	0	100	0	100
2	Only white cement replacement	90	10	0	100	0	100
3	S10G0	80	10	10	100	0	100
4	S30G10	60	10	30	90	10	100
5	S30G20	60	10	30	80	20	100
6	S50G30	40	10	50	70	30	100
7	S70G40	20	10	70	60	40	100

3. Microclimate study area

In this study microclimate of Colombo, Sri Lanka was analyzed. Sri Lanka's climate is classified as Af (tropical rainforest climate) according to the Koppen-Geiger climate classification (Kottek, et al., 2006). It has been reported that Colombo has 0.09 K to 4.4 K higher ambient temperature than selected some rural areas (Perera, et al., 2012). Meteorological data collection was done in Fathima church, Colombo (6.92261, 79.86503). This area is highly metropolitan and has high temperature and humidity values.

The study area is mainly consisting of one large building and a few trees. Almost every ground area is covered by asphalt and consists of a concrete pavement of 135m2 area. Small size CP block was kept in the area and the surface temperature difference with the existing concrete pavement. Figure 1 shows the location and the satellite image of the microclimate study area.

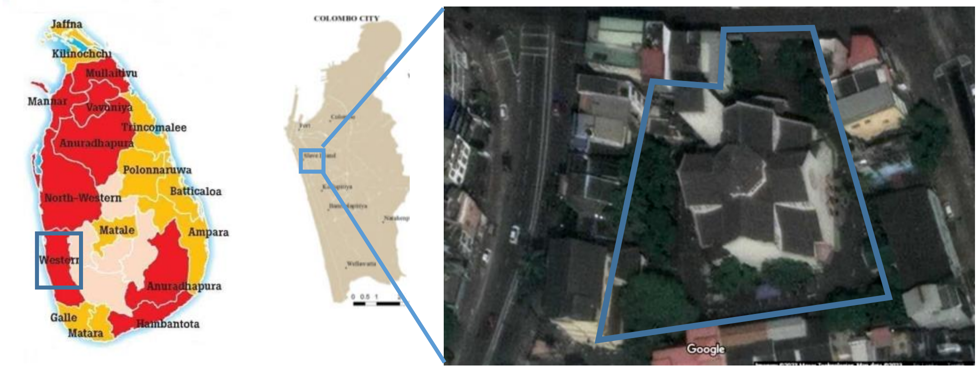

Figure 1: Plan of the study area used for microclimate analysis.

4. Electronic instrument preparation

To measure the meteorological data electronic device was prepared. Relative humidity and temperature were measured using a DHT11 sensor. It contains a capacitive humidity sensor to measure relative humidity while a negative temperature coefficient (NTC) thermistor to measure the temperature. This device contains a micro-SD card module to save the measurements, and DS3231 board to get time and date, and an Arduino Uno to connect each component. Power for the device is supplied by a 12V battery. These types of three instruments were prepared to record meteorological data. Two DHT11 sensors were used in each instrument; one for measuring surface temperature and the other for ambient temperature.

5. Data collection of the study area

Meteorological data collection was done on the 1st of April 2023 from 8.00 AM to 5.00 PM. This day had one of the highest temperature conditions. Surface temperature, ambient temperature, and relative humidity (RH) were measured in three locations in the study area. Ambient temperature was measured from a height of 1.3m as this height has the most effect on the thermal comfort of people. RH and temperature readings were recorded in each 1 minute. Figure 2 shows a picture of the instrument setup in the study area.

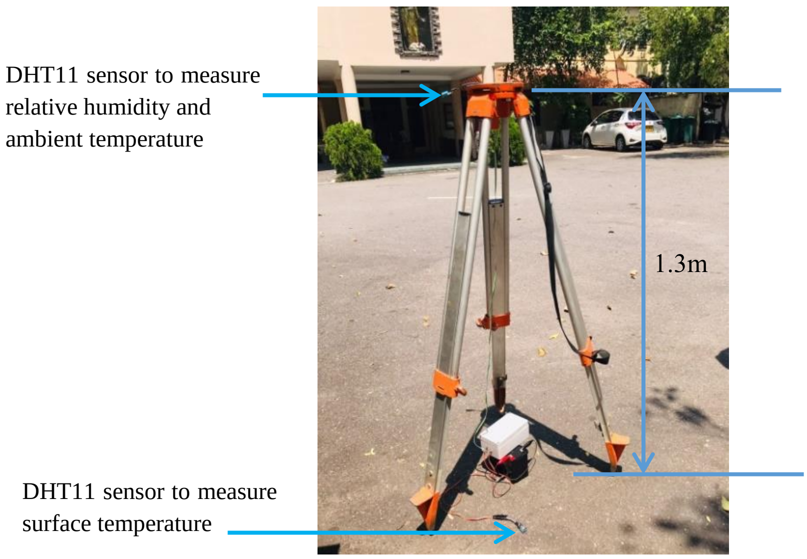

Figure 2: Electronic instrument setup at the study area to record meteorological data.

6. Results

As per Figure 3 compression test results, the Basic mix, white cement replacement mix, and S10G0 design have grained the required strengths. Other cubes have failed to grain the strength of C25 grade, but both S30G10 and S30G20 have grained a normal strength which can be used for normal pavement designs. As per the results, it can be seen when the percentage of slag increases, compression strength is reduced.

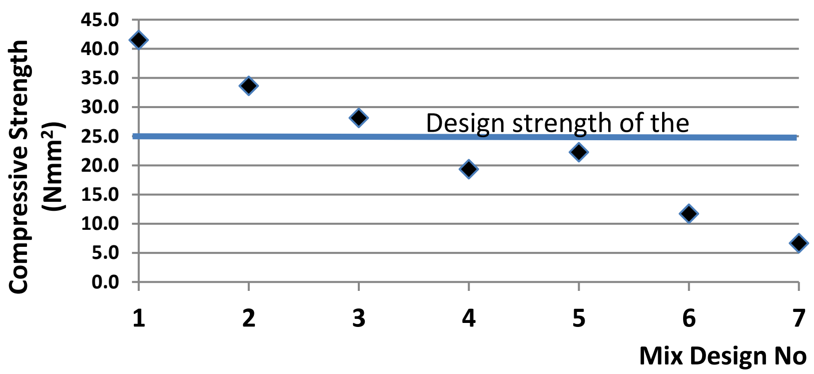

Figure 3: Average compressive strength test results of prepared mix design cubes for CP determination.

Cubes that passed the compression test were kept in direct sunlight and the surface temperature of the cubes was. Results show that the S10G0 cube has a 1.6 K lower surface temperature than the basic mix design. Therefore, it was concluded that the S10G0 cube's solar reflection ability is higher than the other two designs and it was chosen as the optimum ratio for the CP. The Albedo of this CP was measured using a solar radiation sensor and found to have an albedo of 0.455. These results show it has satisfactory reflection.

Small-scale CP was kept in the study area and one electronic instrument focused on it to measure its surface temperature. Another electronic device was kept in the existing concrete pavement. Therefore, a direct comparison of surface temperatures could be obtained.

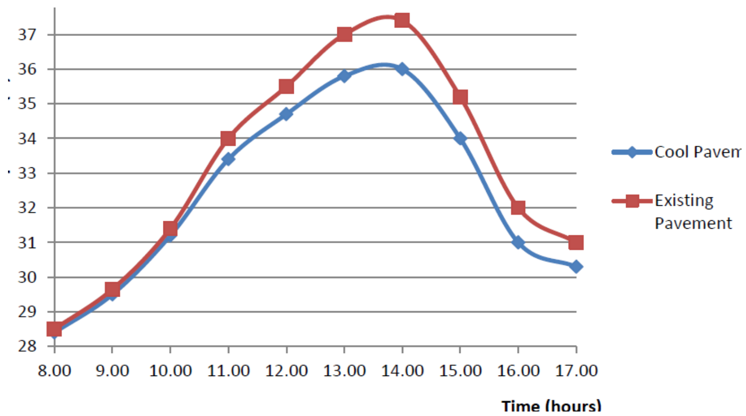

Figure 4: Measured hourly surface temperature variation of CP and existing pavement.

As per Figure 4, CP has less surface temperature than conventional pavement. Hence CP has higher solar reflection ability than conventional concrete pavement. Max temperature reduction occurred in the peak hour of 2.00 PM which was 1.4 K less.

7. Conclusion

It has been found that 10% replacement of slag and 10% replacement of white cement with OPC has the highest solar reflection ability compared to the other mixes. This mix design was chosen as the cool pavement design. Compared to basic C25 concrete pavement, CP has a 1.6K lower surface temperature. Albedo of CP was found as 0.455 using a solar radiation sensor. Microclimate analysis of the study area shows extreme weather conditions occurred at 2:00 PM. At the peak hour of 2.00 PM, prepared CP has grained 1.4K lesser surface temperature than the existing concrete pavement at the study area. Hence this invented cool pavement can be used on a large scale to reduce the urban heat island effect. Thereby thermal comfort of people can be increased while concurrently lowering energy consumption in cities.

8. Recommendation

In this study, only a small-scale CP was constructed, and analyzed the surface temperature reduction, by constructing a large-scale CP, ambient temperature reduction and relative humidity changes can be analyzed, and get more accurate results on mitigating the UHI effect. This is recommended for future research. In the S30G10 and S30G20 mix design, the required strength was not archived but had a high strength of 19.36N/mm^{-2} and 22N/mm^{-2}. It is recommended to reduce the amount of slag and glass proportion of those two mixers, in S20G5, and S20G10 mix designs. These mixed designs may achieve the strength of the C25 grade. If those mix designs achieve strength, more solar-reflective concrete can be introduced, thereby leading to a more effective mitigation of the Urban Heat Island (UHI) effect. Further, ASR testing should be done. In the current study, the aging effect of the concrete pavement was not analyzed. Due to weathering, soiling, and abrasion, concrete pavement gets darker and its albedo will get reduced. This will reduce the solar reflective properties and consequently, the UHI effect could be increased. Therefore, analyzing the aging effect of designed CP is vital; it is recommended to perform an aging analysis in the future.

In the current study, the cool pavement was designed using slag and white cement, adding reflective color pigments that can reflect the infrared rays, into the current pavement design can increase the solar reflection more. Consequently, the UHI effect can be reduced further. This is recommended for future studies.

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APPLICATIONS OF CIRCULAR ECONOMY IN ROAD CONSTRUCTION PROJECTS IN SRI LANKA

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Abstract: The construction industry is one of the largest raw material-consuming industries in the world, as well as in Sri Lanka. The construction industry continues promoting linear practices that rely on 'take, make, consume, and discard'. The adoption of circular economy practices contributes to reducing waste and conserving raw materials on the earth. Despite the existence of circular economy (CE) practices worldwide, Sri Lanka has not fully implemented them. However, such practices have been observed in road construction projects in Sri Lanka, but they are not properly documented. This research aims to assess the level of implementation of circular economy practices in road construction projects. Two road projects were examined through a qualitative study with professionals from the Client, Engineer, and Contractor organizations. Nine in-depth interviews were conducted for data collection, and the analysis was done through transcribing, coding, and categorizing the data. According to the study, the selected road improvement projects have implemented the R strategies of refuse, reconsider, reduce, reuse, repair, refurbish, remanufacture, reuse, recycle, and recover. A circular economy model was developed for road construction projects to serve as a guide for future users. The study findings can assist the construction industry and academia in implementing circular economy practices for road construction projects in Sri Lanka.

Keywords: Circular Economy; Road Construction Projects; R Strategies, 10R Framework

1. Introduction

The term 'circular economy' is only a few decades old; the concept, however, goes back centuries (Crammer et al., 2020). The concept of CE has evolved against the existing pattern of 'take-make-dispose' since the Industrial Revolution (Benachio et al., 2021). The raw materials are extracted from the environment, processed, consumed, and disposed of in the linear economy. According to Benachio et al. (2021), this practice has caused negative impacts on the environment because it loses a significant number of resources during the production or construction processes. In the concept of CE, unsuitable or unacceptable products are reused or recycled to convert to suitable or acceptable quality so that they can be circulated in the material loop without waste disposal (Potting et al., 2017). The precise wording of experts differs, but the following definition of the circular economy generally encapsulates their shared meaning: 'a cyclical, closed-loop, regenerative system in which resource input and waste, emissions and energy leakage are minimized, and redesign and reuse of products are prioritized' (Crammer et al., 2020). CE is positioned as an efficient method for transforming resources into valuable materials for other processes and products (Preston, 2012). According to MacArthur (2013), CE is a process aimed at maintaining products, materials, and components for maximum value of time performance and utility, with the primary goal of eradicating waste. Kirchherr et al. (2017) defined CE as an approach to replacing the end–of–life concept with an economic system that fosters reuse, alternatively reducing, recovering, and recycling in distribution/ production and consumption processes. The model of a circular economy grew out of concepts from the 1970s, including the Rome Club's ‘growth limits' theory (1972), the concepts of Braungart and McDonough's 'cradle to cradle', the performance economy of Stahel, and the regenerative design model of Lyle (ARUP 2016). According to WIKIPEDIA, In the 2010s, several circular economy models were developed that employed a set of steps or levels of circularity, typically using English verbs or nouns starting with the letter 'R'. The first such model, known as the 'Three R principle', was 'Reduce, Reuse, recycle', which can be traced back as early as the 1970s. The concepts of the circular economy have been developed from the principles of 3R (Reh, 2013) towards 10R (Potting et al., 2017), 11R (Izquierdo, 2022), 38R (Kirchherr et al., 2017; Reike et al., 2018) and 60R (Uvarova et al., 2023). The development and application of CE are still progressing (Norouzi et al., 2021). The construction industry is currently the largest global consumer of resources and raw materials, and it is expected that 2.2 billion tons of construction and demolishing waste will be generated worldwide by 2025 (Ellen MacArthur Foundation, 2020). The CE concept evolves to solve critical global issues such as resource scarcity and environmental pollution (Benachio et al., 2021). The CE model is an alternative approach to a linear economy focused on changing the traditional pattern of 'take-make-dispose' and keeping resources in use for extended periods by treating waste as useful inputs (Ellen MacArthur Foundation, 2020). The common value of CE is concentrated in (1) decoupling economic growth from resource consumption, (2) resource efficiency, (3) waste management, (4) sharing, (5) reducing greenhouse gas emission, (6) life cycle assessments; and (7) closing loops (Ness and Xing, 2017). The concept of CE has been gaining momentum in the construction industry, given that using its principles can help reduce the negative environmental impacts of buildings significantly (Smol et al., 2015). However, its adoption in the built environment is still in its infancy (Pomponi and Moncaster, 2017). The reusable and recyclable materials in the construction industry worldwide are still being dumped at landfills, legally or illegally (Wijewansha et al., 2021). Although construction material waste has a high potential for reusing and recycling, it is estimated that only around 40% of the construction and demolition waste generated from the construction, renovation, Repair, and demolition of houses and other infrastructures is currently reused, recycled, or sent to waste to energy facilities, and the remaining 60% is diverted to landfills (United States Environmental Protection Agency, 2018). The implementation of circular practices, particularly in the construction industry, requires immediate attention. CE practices have been observed by researchers in construction projects, but there is a lack of documentation for these applications. This case study research investigates the level of application of CE practices in road construction projects and builds a CE model for road construction projects. These CE models are valuable tools for implementing CE practices in the construction industry.

2. The 10R Principles of Circular Economy

The 10R framework for the CE was developed by Cramer (2017), and this information has been slightly modified by Potting et al. (2017). Cramer again modified this slightly (2020). As seen clearly from the comparison made in Table 1, both Cramer (2017) and Potting et al. (2017) agree with the principles defined in the middle and lower order. However, the higher-order definitions 'Rethink' (Potting et al., 2017) and 'Renew' (Cramer, 2017) have a disparity and a slight difference in order placement. The concept of 'Renew' Cramer (2017), the meaning of 'Redesign product because of circularity' has been replaced by the concept of 'Redesign' Cramer (2020) with the meaning of 'Reshape product with a view to circularity principles.' According to Athapaththu et al. (2016), the issue of unsustainable practices in the construction industry is now being acknowledged. Organizations such as the Sri Lanka Sustainable Energy Authority, the Construction Industry Development Authority, and the Green Building Council of Sri Lanka have taken a more proactive approach towards incorporating sustainability in Sri Lankan construction practice. Sri Lanka has significant work to do to meet global sustainable construction standards. Sustainability-based principles such as CE are new to the Sri Lankan construction industry, as evidenced by the lack of publications.

Table 1: 10R Framework

Cramer (2017)		**Potting et al. (2017)**	
R Principle	Definition	R Principle	Definition
Refuse	Prevent raw materials use	Refuse	Make a product redundant by abandoning its function or by offering the same function with a radically different product.
Reduce	Decrease raw materials' use	Rethink	Make products more intensive (e.g., through sharing products or by putting multi-functional products on the market).
Renew	Redesign product given circularity	Reduce	Increase efficiency in product manufacture or use by consuming fewer natural resources and materials.
Reuse	Use the product again (second-hand)	Reuse	Reuse by another consumer of a discarded product that is still in good condition and fulfills its original function.
Repair	Maintain and repair product	Repair	Repair and maintenance of defective product so it can be used with its original function.
Refurbish	Revive product	Refurbish	Restore an old product and bring it up to date.
Remanufacture	Make new from second-hand	Remanufacture	Use parts of the discarded product in a new product with the same function.
Repurpose	Reuse product but with other functions	Repurpose	Use discarded product or its parts in a new product with a different function.
Recycle	Salvage material streams with the highest possible value	Recycle	Process materials to obtain the same or high or lower-grade quality.
Recover	Incinerate waste with energy recovery	Recover	Incineration of materials with energy recovery.

3. Methodology

According to Yin (2011), a qualitative research approach allows researchers to gain an in-depth understanding of new and emerging topics over other research approaches. A qualitative research approach was chosen to gather data from two road projects, the Badulla-Passara Road improvement project and the Godagama-Bope Road improvement project. The salient features of these two projects are given in Table 2. A semi-structured interview guide based on the 10R framework (Cramer, 2017; Potting et al.,

2017) was developed to gather data. Judgment sampling involves the choice of subjects most advantageously placed or in the best position to provide the required information (Sekaran et al., 2016). Accordingly, the judgmental sample was selected from the directly involved key members of the stakeholders representing the Client, Engineer, and Contractor of both road construction projects. The current CE practices in road construction projects were studied using in-depth interviews to answer the research question, 'What is the level of application of Circular Economy practices in road construction projects?'. The data collection was terminated once data saturation was reached after nine (09) in-depth interviews. Some of the interviews were done physically, and the balance of interviews were done online using the Zoom platform and recorded. Data analysis was done by transcribing, coding, and categorizing data to investigate the CE practices and identify any new circular phenomena connected. Internal validation of data was done with the help of the researcher's observations and the evidence given by the respondents.

Table 2: Case Description

Description	Case 1	Case 2
Project:	Rehabilitation and Improvement to Peradeniya – Badulla – Chenkaladi road -Section from Badulla to Passara (130+800 KM – 150+800 KM)	Rehabilitation and Improvement to Kotte – Bope – road project - Section from Godagama to Bope (16+740 KM – 28+004 KM)
Duration	2017 - 2020	2017-2020
Right of Way width	Varies	50 ft from the center line to either side
Carriageway width	3.3m	3.5m
Hard shoulder width	0.5m	1.5m
Soft shoulder width	0.5m	2.0m

4. Result and Discussion

R strategies that have been practiced in Sri Lankan road construction projects using the 10R framework are discussed below. Section 4.1 describes practical applications of R strategies that could be identified from the study. Those applications are scalable and repeatable. Therefore, a CE model for the Sri Lankan road construction projects was developed from the study, and it is described in Section 4.2.

4.1 R Strategies Applied in the Case Study

R strategies that were discovered in the study include Refuse, Rethink, Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle, and Recover. Application of the Renew strategy could not be identified from the study.

4.1.1 Refuse

Due to the cost and long travel distance of river sand, the contractor used quarry dust, a by-product of a crusher plant, to manufacture concrete refusing river sand. This prevented the use of fossil fuels for transporting sand.

4.1.2 Rethink

A precast modular construction system was introduced for the construction of mass concrete retaining walls, aiming for faster construction in contrast to conventional construction. The use of steel shutters for formworks reduced the waste of wooden formwork. In addition, waste of cement, aggregate, and material waste could be minimized due to the precast construction being done at the central yard. This could be achieved by rethinking the construction process.

4.1.3 Reduce

The roadway excavation required the removal of a significant quantity of weathered rocks, and a large quantity of concrete structures were to be constructed. Then, weather rock was crushed in the crusher and used to backfill the bottom layers of the structures. This action contributed to a reduction in soil excavation, a reduction in land usage for disposal yards, and a reduction in the quantity of disposed soil as unsuitable material.

4.1.4 Reuse
When handing over the construction sites to the contractor, existing properties such as old signboards, cover slabs, and hume pipes were supposed to be handed over in good condition to the client for reuse on other roads.

4.1.5 Repair
It was observed that some culverts, lined drains, kilometer posts, etc., were in reasonably good condition, and only minor damages were repaired and used. This resulted in a reduction in materials: cement, sand, aggregate, and steel. Also, fuel for material transport and machinery usage were reduced.

4.1.6 Refurbish
Existing bridges where abutments and deck slabs were in good condition, but scouring has taken place in the abutments' bases. They were refurbished by constructing jacket walls. This resulted in a reduction in materials: cement, sand, aggregate, and steel. Also, fuel for material transport and machinery usage were reduced.

4.1.7 Remanufacture
When the road's vertical alignment is improved by cutting and lowering the existing road, the existing payment material and gravel were carefully removed from the roadway excavation. They were utilized for the construction of new pavements. As a result of this, there was a decrease in the quantity of virgin materials needed for construction work.

4.1.8 Repurpose
A large quantity of bitumen was used for both permanent and maintenance works on the road. Empty bitumen barrels were used for different purposes, such as fabricating concrete chutes, using them as garbage bins, storing water for curing, submerging concrete lab samples in the water, and using them as safety control barriers after painting. This resulted in a decrease in virgin materials like steel and plastic.

4.1.9 Recycle
Soft/weathered rocks removed from the roadway excavations were crushed at the crusher and used as filling material in structure backfilling works. This led to a decrease in the extraction of virgin gravel material from borrow pits.

4.1.10 Recover
When widening roads, the parts of the trees with no timber value were allowed to be used as firewood for villagers. The reduction of virgin materials like LP gas, hydropower, and crude oil is achieved through this recovery concept.

4.2 CE Model for the Road Construction Projects
Practical applications of the R strategies could be identified in the design and construction stages. R strategies directly helped to reduce the extraction of virgin material from the earth, reduce the amount of material to be discarded as unsuitable for landfill, and reduce the amount of material to be allowed to without use. Figure 1 describes the CE model developed for the road construction projects. The model is limited to similar scalable nature road construction projects in Sri Lanka. Twelve activities as pavement design, structural design, producing of concrete, construction of structures, roadway excavation, demolishing of structures/removing of road furniture, bitumen works, roadway excavation, removing of trees and branches, raw material usage, handling of existing services and precast/modular construction were identified, and they were considered for the CE model.

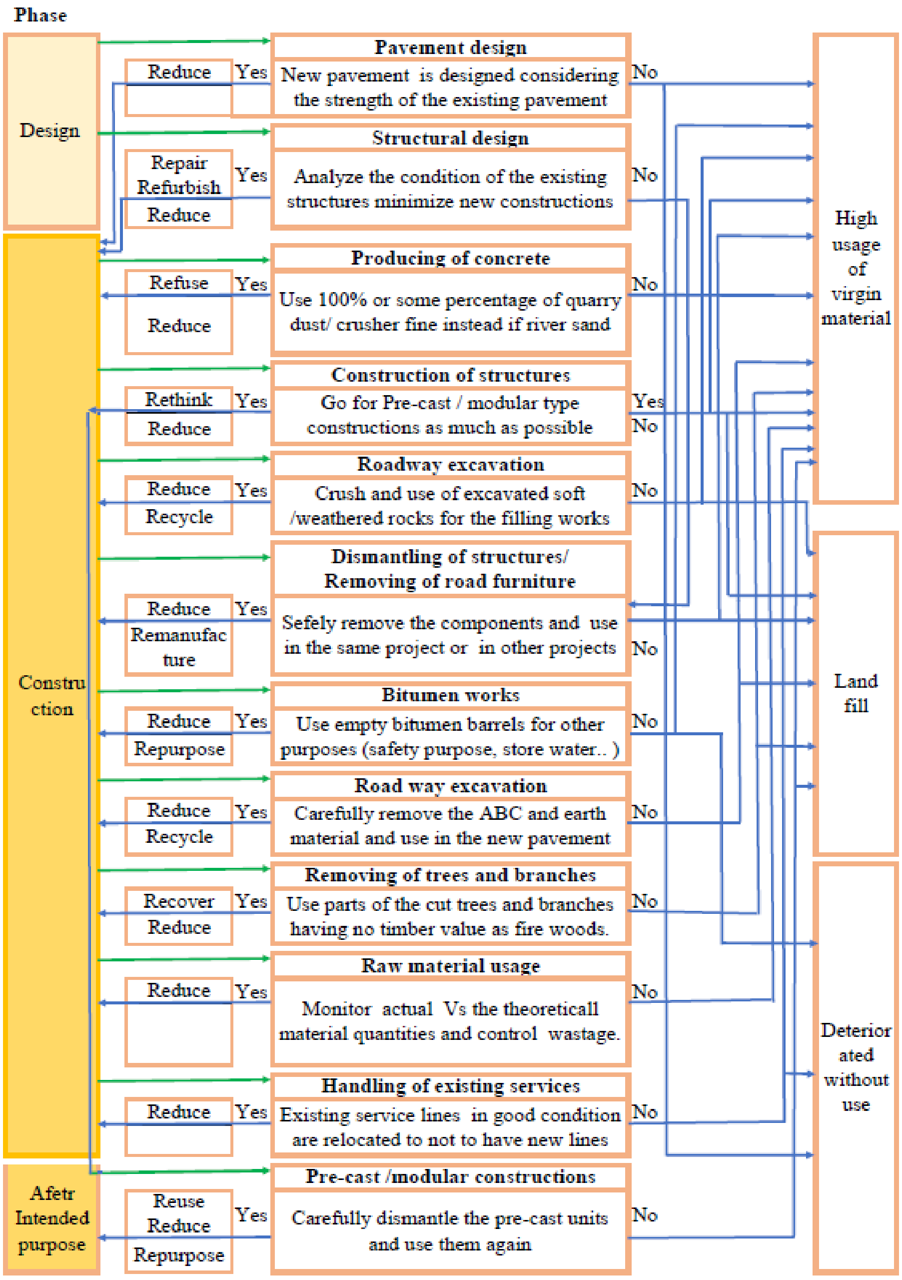

Figure 1: CE Model for Road Construction Projects.

5. Conclusion

This case study research reveals that out of the 10R strategies in the 10R framework, Refuse, Rethink, Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle, and Recover were practiced in the selected two road construction projects. The CE model developed through the findings of this study provides a path for construction professionals and scholars to move in the direction of CE practices during the design and construction stages. It could be found that some valuable CE practices have been applied by the contractors to overcome some material scarcity issues or to gain more financial benefits. Clients have the opportunity to include those practices in contract documents to reap the benefits of R strategies in the future. According to some stakeholders, the 'Value Engineering' provision in the current contract documents regarding road construction only addresses financial benefits. They believed that it would be wise to have such provisions for considering the saving of virgin material and minimizing environmental pollution to encourage the contractors to adopt more and more CE practices. According to this study, some stakeholders are not fully knowledgeable about the concept of CE and its importance. Certain CE practices had to be adopted indirectly through the application of Lean Construction, Project Environmental Management plans, and ISO standards. According to most of the stakeholders interviewed, the precast/modular construction method is the most efficient way to incorporate CE practices in construction projects. Integrating CE practices seems to be a breeze during the planning stage. The implementation of CE practices in road construction projects will result in the saving of virgin material and a decrease in environmental pollution. In conclusion, it minimizes the usage of resources on the planet. As a statutory body, the Road Development Authority can play a vital role by establishing appropriate institutional regulations, promoting training programs, and providing financial incentives to implement CE practices in road construction projects. Further research is necessary to determine the level of virgin material and financial savings in every CE practice.

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A COMPARATIVE STUDY OF THE GOLDEN RATIO AND THE BUDDHIST ARCHITECTURAL PROPORTIONS IN SRI LANKAN RITUAL SPACE

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Abstract: Considerable academic research has been performed which is based on the concept of human mental and physical purification in rituals. However, none of them paid attention to mental and Physical balance using the six senses of humans in Buddhist rituals, structural balance, and representation of microcosms. This study consists of the process that follows to obtain a physical balance for all parties that participate in the ritual. This comparative study is based on the concept of Buddhist architectural proportions, ritual space (microcosms), and Golden ratio. Qualitative and quantitative comparisons were done using archaeological evidence in Egypt, Asian, and Sri Lankan traditions to achieve this objective. The Golden ratio is a mathematical ratio. It is commonly found in nature and has been used in design. The divine proportion has been recognized for thousands of centuries in Egyptian, Greek, and Roman ancient architecture. The shape of the Great Pyramid is based on the same religiously significant idealism of human proportions (Lucus ratio) used to depict the gods and the pharaohs in their reliefs, paintings, and sculptures. This analytical focus is mainly on major Sri Lankan Buddhist rituals (Pirith chanting and other rituals) that restore the well-being of society. Use of space for Buddhist ritual procedure that follows to turn it into architectural proportions in Uposathagara, Relic of Tooth, Dagaba, Image house, and Bodhigara, to achieve physical balance. These were rigid geometrical, highly formal, and symmetric Architectural layout arrangements. This study analysis is mainly on the effect of a sustainable environment on the audience which is based on the concept of mental and physical balance using the six senses of humans in Sri Lankan Buddhist rituals.

Keywords: Architectural proportions; Ritual space; Sri Lankan Buddhist ritual performance; Mental and physical balance; the Golden ratio.

1. Introduction

1.1 Geometry / Ritual Space

The description of shrines of deities built during the pre-Buddhist era is confined only to the chronicles and no archaeological evidence to substantiate these descriptions. Therefore, the earliest monuments in Sri Lanka coincide with the beginning of Buddhism in this country and it is correct to say that all parts of Sri Lanka flourished with the inspiration from the teachings of Buddha (Rahula (1956)). The origin of Buddhist temple architecture begins with the temple development in the city of Anuradhapura. The earliest known dwelling for the Buddhist monks in Sri Lanka included that of Mahinda Thera and his companions who introduced Buddhism and of the earliest batch of monks (Rahula (1956)). As history unfolded, Sri Lanka was subjected to various foreign invasions from time to time. These resulted in even the administrative capital of Sri Lanka being shifted from place to place Polonnaruwa, Dambadeniya, Yapahuwa, Athugala, Gampol, Kotte, and Kandy.

The early traditional temples were located away from the city or village, but these locations facilitated circumambulation to the ritualistic, worshiper, and pathways led to connected to temple and village. The major worshiping elements are the Bodhigara, shrine, and Dagaba were located close to the public entrance (Rahula (1956)). Some were arranged as isolated monastic temples and in Tabatha viharas which are located on the outskirts of the city. The squared quadrangle consists of an elevated platform with a retaining wall. This quadrangle usually has four entrances facing the cardinal point, having the main entrance generally facing the south. The buildings contained within the sacred quadrangle are Uposathagara (Chapter house), Stupa, Bodhigara, and Image house. The Bodhigara would be in the southwest or first quadrant, the Image house in the northwest or second quadrant, and the Stupa in the southeast or fourth quadrant (Silva (2004)). This arrangement applies to all the examples except Toluvila and Kaludiyapokuna. At Toluvila the stupa is placed in the first quadrant (Silva (2004)). Those that are built within the monastic boundaries of a pancavasa vihara, have to be built in water, thus providing a jala-sima to scared building as though it were an island. However, the terraced nature of the plan offers a superficial similarity to the temple mountains of Cambodia and Java (Silva (2004)).

Abayagiri ruins known as the ‘Westerner Monasteries’ most probably constitute the Tapovana (ascetics grove) of the chronicles and Hocart sees a similarity in the architectural plan of these monasteries with those under survey (Silva (2004)). But in the Polonnaruwa era, these were rigid geometrical, highly formal, and symmetrical layout arrangements. Most of Uposathagara which is situated in the center of the temple (Brahma pada), is a sacred place. The Stupa containing a body relic of Buddha, which represents the cosmos, stands at the highest position in the temple environment (Wickramagamage (2010)). The calm serene, tranquil, and sacred environment provides the background necessary to achieve the purpose of the Buddhist environment that exists in the temple is their contribution of the environment qualities. The Bo-tree which spread over a large area of the temple creates quite gloomy. This was the most attractive and richly emphasized aspect of the environmental qualities and in itself expresses a feeling of strong separation from the secluded world to the religious world. Pilgrims come to the temple with the expectation of seeking an end to many of their problems. In such cases, they start their journey through the sacred place of worship (Rahula (1956)).

The Golden Ratio and Lucus Ratio are mathematical ratios. Divine Proportion (1.618.) has been recognized for thousands of centuries: from the Pyramids in Giza to the Parthenon in Athens; from Michel Angelo’s The Creation of Adam on the ceiling of the Sistine Chapel to Da Vinci’s Mona Lisa. When considering geometry of space, there are alignments in between the Eye of God in Golden spiral (Starting at zero, the sequence is: 0, 1, 1, 2, 3, 5, 8, 13, 21, 34, 55, 89, 144… and so on) and Deva pada in Sri Lankan architecture.

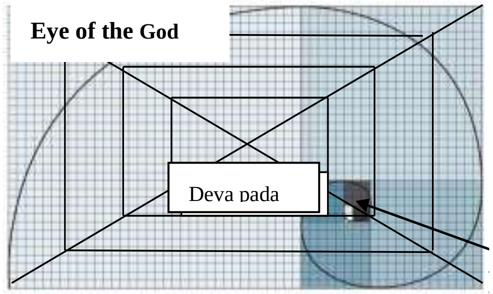


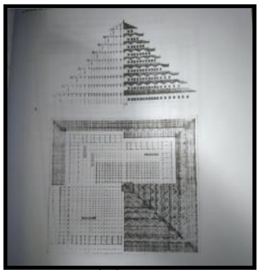
Figure 1: Space alignments between the Eye of God in Golden spiral and Deva pada in Sri Lankan Buddhist ritual space.

When considering the planning concept of the 'Pandavas' monasteries that have been codified in the treatise, the Vastuvidyasastra by Manjusri, one can draw a series of generalizations. The twenty-four plans presented together with the variants due to their facing the four directions, and the reverse forms, the total of the designs amounts to forty-seven. The 'Sahba' has more often than not held the central position in the group of the five holy units and therefore, occupied the Brahma kostha in twenty-four instances. It is for this reason that they are inclined to suggest that the Sabha was the most sacred (Silva (1990)). of the edifices of the raised court and therefore, used for all Sanghakarma such as the uposatha, the ordination, the audience of special dignitaries, and even for symbols of representation of Load Buddha, special sermons and pirith chanting at the center of the architecture (Mandapa). The distribution of this edifice is about twenty-five or nine padas (Silva (2004)).

2.1 The Design of the Great Pyramid of Khufu.

The Egyptians built this massive pyramid based on some important specific design. The perfection of the exterior proportions is precisely matched in the interior chambers and corridors and works in exact accord, more ever, a collaborative piece of evidence that the design exhibits the same proportions as the Great Pyramid. The empirical evidence of the surveyed dimensions presented here repeatedly reveals the presence of the golden ratio and by implication (but with slightly less correlation) the Pi ratio (Bartlett *et.al.* (2014). It would also suggest that the ancient Egyptians intentionally built the Great Pyramid to exhibit the mathematical concepts of either Φ or π or perhaps to reflect both. Yet there doesn't seem to be any good reason or conclusion that it was unless to demonstrate to the future an advanced mathematical knowledge. A notion that would seem, in Christoper's opinion, rather oblique to their other very real spiritual and funereal concerns (Bartlett *et.al.* (2014).

Unlike the golden ratio, a visual proportion that is mentioned as an ideal relationship in virtually every text on art and design, it would be hard to argue that pi is an aesthetic proportion for the visual arts (Bartlett *et.al.* (2014). Christoper believes pi produces an aesthetically pleasing visual result, while on the other hand, the golden ratio has a strong following in the arts. That even the mathematically interesting golden ratio proportion has any implicit aesthetic beauty is debatable and psychologically hard to prove. Nevertheless, as a basis for compositional design, the Golden ratio has, unarguably, the important quality of bringing harmony and unity through self-similarity and continuity of proportional divisions. Christoper has published on the geometry of composition in painting notably. Decoding Interior in Smithsonion's American Art Journal where Christoper detailed Porter's compositional use of √Φ his most recent paper. Huylebrouk called the 'chi ratio' rectangle (1:1.356) and its applications in the geometrical composition of painting. It is a proportion that has the same generative properties as the golden ratio rectangle, dividing into similar 1.356 rectangles and golden ratio rectangles ad infinitum (Bartlett *et.al.* (2014).


(a)

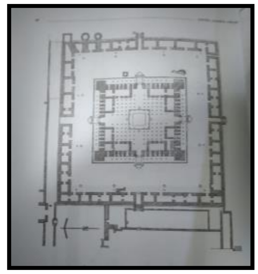

(b)

Figure 2: pyramid architectures (a- Design of Lovamahapasada (Sri Lanka),b- Baddasimapasada Foundation (Sri Lanka)).

2.2 Design of Temples

2.2.1 Temples with Stepped Pyramid (Prasada) Roof

The Brhadesvara Temple, Thanjavur (eleventh century) some fifteen stories, 66 m high is the grandest example of a square-planned temple. The garbhagara with the linga shrine at its center, has only one entrance but the surrounding passage has entrances facing all four directions. Pavilions adorn the floor levels externally and aedicular niches surround the substantial, slightly stilted rubbed dome at the pyramid (Silva (2004)).

Darmaraja Ratha is a four-story monolithic seventh-century building with a stepped pyramid or Prasada roof, 8.5 m high. The ground floor consists of a single hall that contains the ritual objects of worship. The upper stories of the stepped pyramid were non-functional. Pavilion-like structures decorate each floor level at the edge of the slab. The roof ends of these pavilions (Silva (2004)).

Mamallapuram on the southeast coast of India, south of Madras, several huge granite rocks were carved into small temples or raths during the Pallava period. The five-storey Shore Temple at Mamallapuram on the other hand was built in stone masonry in the eighth century. Each has a garbahagara in which the Sivalinga is housed, and a small mandapa, the whole surrounded by a heavy outer wall with little space between for circulation. At the rear are two shrines facing opposite directions. The inner shrine of Kastriyasimnesvara is reached from the ambulatory passage while the other, dedicated to Vishnu, faces the outside. The outer wall of the shrine to Vishnu and the inner side of the boundary wall is extensively sculptured (Silva (2004)).

The word 'pasada' suggests a stepped pyramidal shape in Sri Lanka. The Lovamahapaya of the third century B.C., erected in the Mahavihara of Anuradhapura, still retains the stone columns of the ground floor, at a height of 5.4 m The nine stories of this structure, apart from its ground floor, were all built of dressed timber, beams rested on the massive stone pillars, and extended out into a wide eaves projection. The Lovamahapasada had 1600 [72 m X 72 m)] and the Baddasimapasada retained 252 (32 m X 32 m) (Wanigadewa et. al. (201). The overall length and breadth of this square building was approximately 75.7 m (Silva, (2004)). The construction capacity of Sri Lankan craftsmen in wood, reaching the height of the building of 49m is indeed spectacular. The square multi-storeyed type, with an internal stairway, includes such edifices as the Lovamahapasada and the Baddasimapasada (10 to 12 floors), both of which had internal vertical communication links. The sitting capacity of the Lovamahapasada could have been as high as 9000 monks, while that at the Baddasimapasada was around 2000 (Silva (2004)). The Mahawamsa refers to an inner court and an internal veranda, which suggests that the Bronzen palace could well have been like the Baddasimapasada (7.2 m X 7.2 m) that has a distinct enclosure with a series of cells surrounding the central edifice and a courtyard (18 m X 17½ m) in between (Premathilake (1964)). These distinctive characteristics seem to signify the true hallmark of this square, multi-storeyed pyramid type of Upostha in Sri Lanka (Bandaranayaka (1974)).

The rectangular multi-storeyed type with an external stairway has a designed stamp that is distinctly recognizable. The Rathnapasada at Abayagiriya, the pasada of Jethavana, Mirisaweyita, Yatala, and Thissamaharama, all express these marked characteristics. Abayagiriya monastery which had 5000 monks could accommodate only 1500 within the inner unit. The double-storeyed uposathagaras consist of two specific types in panchavasa.

Table 1: proportions of rectangular Uposathagara (Sri Lanka)

Uposathagara	**Length (m)**	**Width (m**	**ratio**
Tholuwila	15.3	12.1	5/4 -1.2
Wijayarama	13.3	10.9	5/4-1.2
Puliyankulama	14.7	11.2	5/4 -1.2
Pachinathissa	13.9	11.6	5/4 -1.2
Pankuliya	10.6	8.18	5/4 -1.2

Premathilake (1964).

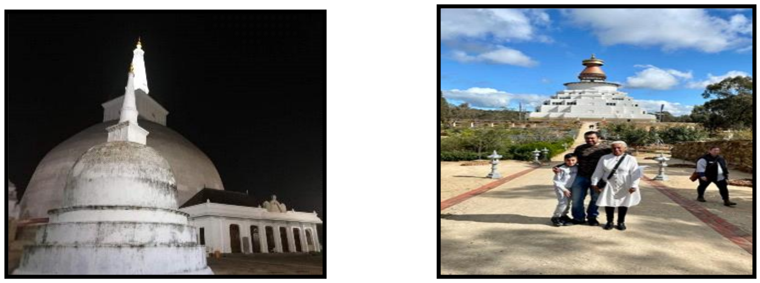
A Stupa has a more complicated shape than a Pyramid, and ancient builders of Sri Lanka have shown much technological as well as management skills in the construction of large Stupas. There was strict supervision and quality control. Mahawamsa gives elaborate descriptions of the construction of great Stupas like Ruwanweliseya (Ranweera (1998)). The Stupa are oriented along North-South and East-West axes, and setting out has been done very accurately. In Abayagiri (present height 73.0 m, outer basal ring diameter 108.8 m) orientation of the boundary walls is within 1.5 degrees accuracy and the top of the spire is almost in the same vertical line passing through the center of the base (maximum shift is 23 mm) (Dampegama (2001)).

Great care has been taken in selecting the sites and laying out the foundations. Most stupas have been founded on rock and for others, elaborate preparations of the foundation have been made. The dome is a perfect solid of revolution, which is an ellipsoid for Jetavana and a paraboloid for the Abhayagiri. In some cases, for the inner regions of the dome brickbats and earth were used, while the outer regions were of strong large bricks. (Ranaweera (2001)). There would have been efficient construction management to handle material and labor in the construction of mega Stupas (Silva (1990)).

Table 2: proportions of main Stupas in Anuradhapura (Sri Lanka)

Stupa	**Shape**	**Estimated height (m)**	**Height (m)**	**Radius (m)**	**Circumference (m)**	**diagonal Radius**	**Height Radius**
Ruwanweli saya	Bubble	55.0	91.4	45.1	290.0	71.1/45.1 1ශ57	55ය45.1 1ශ21
Jetawana	Dhanyarasi	122.1	70.7	56.0	347.5	1ශ60	1ශ25
Abayagiri	Dhanyarsai	105.0	73.0	53.6	108.8	1ශ68	1ශ36

Ranaweera (2001) / (Dampegama (2001)



(a) (b)

Figure 3: Stupa (a- Ruwanveliseya (Sri Lanka), b-Pagoda (Australia)).

According to Smither's report, the height of the major stupa ruins was Ruwanveliseya-54.5 m. (Silva, W.N.G. (2007)).

Table 3: proportions of Stupas in Sri Lanka

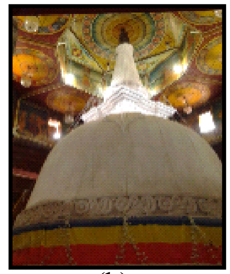
Stupa	**shape**	**Height (m)**	**iameter (m)**	**Diagonal ---------- radius**	**Height -------- radius**	**slope**
Thuparama	Bell	18	18	2.3	2.1	64^{o}
Thissamaharama	Bubble	45.9	43	2.3	2.1	64^{o}
Rankothvehera	Dhyanrasi	61	56.7	2.3	2.1	64^{o}
Kirivehera	Dhyanrasi	21.3	24.3	2.0	1.8	61^{o}
Mirisawetiya	Bubble	55	43	2.7	2.5	67^{o}

2.2.2. Temples with Pagoda Roof

The Chergaon Temple, Chamba, is built almost entirely of wood and nestles on the slopes of the Kashmir foothills. It includes the intrinsic elements of a Hindu shrine with a three-storey garbhagruha. The roof, over Garbhagruha, is circular although the plan is square (Silva (2004)). The Temple of Mahadeva, Patan, probably dates from about the seventeenth century and is typical of the pagoda-roofed temples of Nepal. It has two stories, the timber structure elaborately carved, and stands adjacent to the stone, sikhara-roofed temple of Krishna. The principal square of Patan is surrounded by these elegant timber-framed buildings (Silva (2004)).

This encirclement comes from the shape of the house itself. Abandoning the architecture of present-day theaters will be rented some kind of born or hanger rebuilt along a line culminating in the architecture of some churches, holy places, or certain Tibetan temples. The building will have special interior height and depth dimensions. The auditorium will be enclosed within four walls stripped of any ornament, with the audience seated below, in the middle. In addition, overhead galleries run right around the circumference of the room as in some primitive paintings (Artaud (2010).

(a)



(b)

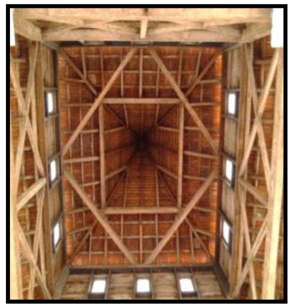
(c)

(d)

(e)

Figure 4: vatadage (ritual space) (a- Attangalla vihara vatadage (Sri Lanka), b- centered stupa, c, d- Dadagamuwa vatadage (Sri Lanka), e Gadaladeniya (Sri Lanka)).

The ‘vatadage’, or Rotunda type sheltered smaller stupas of approximately 12.1 m in height. These round structures still retain the circular sets of columns that supported the timber roof. Every set of circular set of columns that supported the timber was interlocked to form a perfect timber ring beam. The innermost ring supported a steeply angled set of rafters, which pressed against the uppermost timber ring and was held fast at its pinnacle by a timber boss (kanimadala). That rested well above the pinnacle of the stupa within. The rest of the rafters were at a shallower angle radiating, in line with the uppermost set, filling in the wider gaps where necessary, and spanning from one set of timber ring beams to the other. There was a splay on the roof at critical intervals to provide clearstory lighting for the interior, especially over the brick wall of the inner chamber. The outer podium had an opened verandah and free space beyond for circumambulation. The inner shrine of the stupa had four entrances, with Buddha images facing each doorway. Offerings by pious pilgrims were placed on flower altars positioned between the Buddha shrines (Silva (1990)). The traditional construction techniques for square peaked roofs are also indicated in another illustration. A subsequent growth of this roof style, which changed from a circular form that originated in the 2nd century B.C. and was abandoned around the 12th century A.D., had been revived in the square or rectangular form, after the 12th century. These roofs also covered a stupa house, which was modest and simple. However, the roof details and the radiating rafters are seen in the examples illustrated (Silva (1990)).

(a) (b) (c)

Figure 5: Structures of the temple (a- Minuwangoda raja maha vihara- Dhamsabha mandapa (Sri Lanka), b- pyramid-shaped roof and center, c- centered pirith mandapa.

2.2.3. Lucus Ratio

The ancient Egyptians had no implicit intention of incorporating the geometrical and mathematical theories of either Φ or π, but the shape of the Great Pyramid was based on the same religiously significant idealism of human proportions (Lucus ratio) (Starting at zero, the sequence is 0, 1, 1, 3, 4, 7, 11, 18, … and so on) used to depict the gods and the pharaohs in their reliefs, painting, and sculpture. The studies mentioned above corroborate the view that the Egyptians and a predilection for simple golden ratio proportions in their art and architecture. Since the figural formula they employed gave a primary golden ratio division of 7:11 then it follows that if the same human proportion was used for the design of the Great Pyramid the golden ratio would appear as its consequence rather than its cause (Bartlett *et.al.* (2014).

The architects of Khufu's vast Pyramid in choosing its slope would not want to encounter the structural problems of the bent pyramid and they would surely want to follow the architectural and artistic traditions of the time. The choice of one angle over another would seem to be of paramount importance for many reasons, and it would need to be harmonized in the interior dimensions. Designing the Great Pyramid to correlate with the Egyptian canon of proportion used in their art for millennia had to carry the same religious and cultic importance as the depiction of the figures themselves (Bartlett *et.al.* (2014).

For the ancient Egyptians, the concept of renewal, the idea of generative continuity, and permanency of corporeal life after death were the all-important religious concerns and the pyramids exemplified this undeniably, the Pyramid were built to provide this continuity from life to the afterlife, and so the Φ concept of self. Similarity and generative continuity as it appeared in their depictions of the human figure, he believes, seems a natural choice for the design of Khufu's tomb (Bartlett *et.al.* (2014).

(a) (b)

Figure 6: Human proportions and architectural proportions (a- Herbal tough (Mahavihara ancient hospital in Sri Lanka), b- pirith mandapa proportion (Dova vihara in Sri Lanka)).

2.2.4. Horus naval height Φ proportion

Significantly the navel at square 7 aligns with the position of the royal burial chamber. Similarly, the airshafts meet at the point of the base of the Royal burial chamber which is 11/18 of the horizontal distance between the cuter openings of the two shafts. If we position the pharaoh's mummy, then the offset Royal burial chamber is exactly. In vertical alignment with the navel of the standing figure. This offset from the center of the Pharoh's chamber has been puzzling to many, especially since, the so-called Queen's chamber below is off at a perfect center. The significance of the modules of 7:11 rectangles is hereby explained. The alignment of the navels of the sitting and prone figures perfectly determines the location of the burial chamber, the Khufu's Great Pyramid (Bartlett *et.al.* (2014).

2.2.5. Hospitals (Rogalaya)

The outer set of squares is absent in the vihara layouts of the nine kosthas as in the case of the Sithalagulmarama, Bhujangahanarama, etc. Here the functional and religious edifices are all in one square surrounding the central Brahma kostha. The outer squares retained the main and side gates and some of the service elements. The hospital (rogalaya) has always been placed in the outer square and often in northern Kosta, Mukhya (Silva (2004)).

(a) (b)

Figure 7 : **(**a)- Mihintalaya ancient hospital (A. C. 853-889) (Sri Lanka),(b)- Mahavihara rogalaya (Sri Lanka).

3. Materials and methodology

Qualitative & Quantitative research methods are used in this study. Qualitative research method: Visiting Sri Lankan Buddhist rituals, studying techniques, and discussions. Watching Eastern and Western rituals. Quantitative method: Primary resources: Archeological evidence, archeologists' notes, and books, studying of the structural balance of restored Stupa, Bodhigara, Uposathagara, Srine house, Sabha, and ancient hospitals. Studying the structural balance of Asian Buddhist archeological structures, Pyramids, Italian cultural buildings, and the Golden ratio. Secondary resources: Library resources, research papers which are published on the internet about designs of Buddhist architecture, designs of the exterior and interior architecture of pyramids, golden ratio and Lucus ratio, literature on rituals, and Buddhist ritual books.

3.1. Calculations

In mathematics, two quantities are in the golden ratio, if their ratio is the same as the ratio of their sum to the larger of the two quantities. The figure on the right illustrates the geometric relationship. Expressed algebraically, for quantities a and b with $a>b>0$, $a+b/a = a/b = \Phi$. According to the history of mathematics 'pi' was first understood and used by the ancient mathematician in Egypt, two to three thousand years ago, due to its frequent appearance in Geometry. Where the Greek letter phi (Φ) represents the Golden ratio. It is an irrational number that is a solution to the quadratic equation (Bartlett et.al. (2014).

$$x^2 - x - = 0 \quad (1)$$

$$\Phi = 1+\sqrt{5}/2 = 1.618 \quad (2)$$ (Bartlett *et.al*. (2014).

3.2. Theory

The other popular alternative geometrical design theory in contention has a reasonable fit to the empirical measurements. The π theory makes the height of the pyramid equal to the radius of the circle that has a circumference equal to the perimeter of the base of the pyramids, 4 x base □ 2 π ($\pi = 3.14159$) so using the most recent estimate of the base as 230.329m, then the perimeter is 921.316m which it divided by 6.2857 gives a height of 146.5733m (using cubit dimension) 4 x 440 = 1760□2 x 22/7 x 28. This certainly is very close to Lehner's estimate of height at 146.59m. except there is an inherent issue. If the Great Pyramid exhibits the dimensions of the golden ratio so that $(0.618) = 1/\ \Phi = (\pi/4)^2 = (3.1416/4)^2 = 0.617$. The Φ (Kepler) theory gives a theoretical angle of 51° 49´ 38 (51.827°). The Φ and π theory results in such a great connection to the primary design theory because of this close similarity (Bartlett *et.al.* (2014).

4. Conclusions

- Nearly similar ratios can be seen in Buddhist and Hindu architectures in eastern countries as well as Egyptian and Greek architectures.

- Alignments can be seen between the Eye of God in the Golden spiral and Deva pada in Sri Lankan Buddhist ritual space.

- Pyramid (the Great Pyramid/ Uposathgara / Stupa/ Vatadage/ Pagoda) architecture, which is used as the sacred point, had been created by architects in both traditions.

- Buddhist rituals that are performed in Sri Lanka can be used for the mental and physical balance of humans by using ritual space (temples /ancient hospitals).

5. Future works

These ratios and proportions can be used for further research to create more sustainable ratios or proportions. These ratios can be applied for structural stability. These architectural proportions can be used in modern sacred spaces and architecture. These structural balances can be used for the construction of future meditation centers, stress relieving centers, future hospitals, and non-communicable diseases (cancer) palliative care units. This sustainable environment can be applied to the well-being of society.

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EMISSION REDUCTION POTENTIAL AND LAND-USE IMPLICATIONS OF DECARBONISING THE POWER SECTOR IN SRI LANKA

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Abstract: Sri Lanka has ambitious plans to increase the share of renewable energy and introduce natural gas in the power sector to reduce GHG emissions as part of the Paris Agreement. Meanwhile, the agriculture sector and land-use sector come up with a different set of policies for example to increase domestic crop production and keep the forest cover in Sri Lanka to 30% of the land area. These policies may have constrained the availability of land for renewable energy development. As such, there are several interlinkages of policies made independently for different sectors in Sri Lanka which are not clearly understood. The Climate, Land-use, Energy, and Water Systems (CLEWs) is a well-established framework that allows the analysis of interdependent sectors in a country or region for better-informed policymaking. This paper presents an initial attempt to develop a CLEWs model for Sri Lanka. The study focuses on the energy sector policies that are existing, an Existing Policy Scenario, and a Perceived Policy Scenario with ambitious plans for renewable energy development. These scenarios were compared to a least-cost business-as-usual (BAU) scenario. The preliminary results showed that ambitious renewable energy deployment requires 7.6% of the available grass and scrublands which may lead to potential conflicts for agriculture, forestry, and economic development activities.

Keywords: CLEWs; Policy analysis; Renewable energy; NDC

1. Introduction

In 2015, the Paris Agreement was signed by 196 countries within the United Nations Framework Convention on Climate Change (UNFCC, 2015). The long-term objective of the agreement is to keep the increase in global average temperature well below 2oC and limit the increase to 1.5 oC. Under the agreement, each country must determine and regularly report on their contribution to mitigating all Greenhouse Gas (GHG) emissions.

As a part of the Paris Agreement, Sri Lanka (LKA) has committed to increasing the forest cover to 32% of the total land area and reducing GHG emissions by 14.5% from 2021 through 2030 from power (electricity generation), transport, industry, waste, forestry, and agriculture (Ministry of Environment, 2021). LKA expects to achieve its Carbon Neutrality by 2050.

Sri Lanka's (LKA) energy sector is import-dependent; 43% of the primary energy supply is imported Petroleum (both crude oil and refined petroleum) products (SLSEA, 2019). In 2018, about USD 4 billion was spent on fuel imports, which approximately accounts for about 33% of LKA's non-petroleum export earnings (Asian Development Bank, 2019). Just over one-third of LKA's primary energy use comes from indigenous biomass. The rest is from petroleum, coal, and renewables including a major share from large hydro. Power generation in LKA is dominated by coal and oil followed by large hydro and other renewable sources as shown in Figure 1.

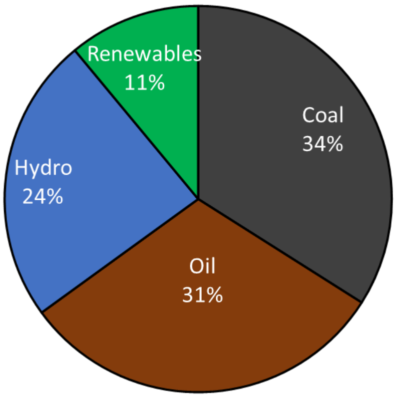

Figure 1: Power generation by source (CEB, 2021a).

The country is 99.9% electrified, the highest rate in the South-Asian region. The peak power consumption was approximately 2,717MW whereas installed power capacities are about 4,400MW (CEB, 2021a). Coal is imported for the sole purpose of power generation whereas petroleum is used in both the transport and power sectors. Recent explorations indicate that the country has natural gas and other petroleum reserves in the northwest of the Island (Asian Development Bank, 2019; Ministry of Highways Road Development and Petroleum Resource Development, 2019). However, commercialization of these reserves is not expected in the short or medium time horizon.

Out of the 65,610 km2 of land in LKA, 35% is used for agriculture and about 30% remains as forests (Department of Land Use Policy Planning, 2014). Home gardens account for 18% of the total land area. The main agricultural products in LKA are rice/paddy, tea, rubber, and coconut. About 70% of the land available for agriculture is used for these major crops. The overall agricultural production contributes to about 7% of LKA's GDP whereas the sector has been the livelihood for more than 1.65 million smallholder farmers.

In 2019, LKA's total GHG emissions were 41.4 $MtCO_2e$ (Ritchie et al., 2020). The transport and electricity sectors contribute to ~58% while agriculture contributes to 14% of total GHG emissions constituting the three leading emitting sectors of Sri Lanka. The industrial sector contribution accounted for ~8% and non-combustion emissions including waste, land-use, and land-use change accounted for ~13%.

The national energy policy and strategies of LKA, building on three principal pillars; energy security, equity, and sustainability, are expected to pave the way to realize the vision of LKA in achieving carbon neutrality and complete transition of all the energy value chains by 2050 (Ministry of Power and Energy, 2019). Prioritizing indigenous energy resources including vastly untapped renewable energy resources, the policy also focuses on aspects of climate change. Similarly, the National Policy on Natural Gas emphasizes the sustainable use of natural gas as an alternative source of energy and industrial input which can be expected to bring long-term economic benefits (Ministry of Highways Road Development and Petroleum Resource Development, 2019).

The agriculture sector's existing policies give prominence to domestic production, maximizing the sector's resource efficiencies and modernization requirements (Ministry of Agriculture, 2007). The proposed expansion of the sector is expected to create some pressure on natural resources including forest lands which are being compromised for other socio-economic development needs (Ministry of Agriculture, 2021).

Traditionally, national energy policies and agriculture policies for example are designed and implemented independently. However, in the context of climate change mitigation, they become closely interlinked through land-use and water systems. Therefore, policy-making can benefit from an evidence base provided through analysis that considers those interlinkages.

This study describes the first attempt made at using a modeling tool that provides a combined analysis of climate, land use, energy, and water systems in Sri Lanka. The preliminary studies prioritized energy policies with limited interlinkages with other sectoral policies. The outcomes of the analysis were used to describe the indicative benefits of using such an approach for policy-making in Sri Lanka.

2. Multi-sectoral policy objectives and scenarios

2.1. New energy policy context

So far, energy policies for LKA (Ministry of Power and Energy, 2019, 2015) emphasize the need to improve energy security through diversifying primary energy sources and prioritizing the need for developing indigenous resources. Furthermore, the national policy framework ('Vistas of Prosperity and Splendour') (Government of Sri Lanka, 2020) introduced in 2020, emphasizes the power sector's strategic direction to increase the share of renewable energy to 70 percent of the total energy mix by 2030. Further, this policy also signifies the natural gas transformation. Both these initiatives emphasize the urgency for a significant diversification of the existing energy mix, reducing the dependency on fossil fuel import as well as decarbonization.

At present, the policy related to the electricity sector in Sri Lanka is governed by the "General Policy Guidelines on the Electricity Industry" as amended in 2021(Ministry of Power and Energy, 2021), which are stipulated under section 5 of the Sri Lanka Electricity Act (Government of Sri Lanka, 2009). The policy directs that 70% of the electricity generated in 2030 come from renewable energy sources, and to neutralize the net carbon emissions of power generation by the year 2050.

Meanwhile, the focus on increasing domestic crop production has resulted in more land being converted for agricultural purposes, one of the major causes of deforestation in LKA. Further, renewable energy development is already facing hurdles due to competing land use priorities and it is expected to escalate in the future. Therefore, integrated land use planning is a key strategic intervention that can facilitate multi-sectoral objectives.

These multi-sectoral policy objectives are summarised as the following.

- How can increasing electricity demand be met by indigenous resources (i.e. renewable energy)?
- How can increased renewable energy share help the country to diversify its energy mix, and reduce emission footprint, and cost of energy?
- What is the overall impact on agriculture in terms of land use constraints and development needs?

To attempt to answer the above questions, a multi-resource systems model for Sri Lanka, inclusive of the Climate, Land, Energy, and Water systems (CLEWs) is developed.

2.2. An overview of the scenarios analyzed.

The modeling objective of the exercise was to examine how renewable energy and natural gas penetration can increase the power sector's fuel diversity and its implications on costs (investment + operation), land use, and the environment (GHG emissions). The scenarios are derived from the existing strategic policy directions detailed in the earlier sections, thereby, the model and its results could facilitate an evidence base for decision-making. The scenarios are defined around existing energy policies as priority GHG mitigation efforts by the government are expected to be in this sector and in addition, due to data availability. Three scenarios are defined,

1. Business as Usual (BAU) Scenario envisages a least-cost solution for energy supply that meets the future energy demands in Sri Lanka.

2. Existing Policy Scenario provides the base of current policy direction in LKA, i.e., to have at least 50% of the electricity generated in 2030 come from renewable energy sources. In parallel, an additional dimension on energy security poses a constraint here, that the firm electricity generation capacity by 2030 needs to come 30% from Natural gas, 30% from coal, 25% from large hydro, and 15% from oil, and the remainder from firm renewable energy.

3. Perceived Policy Scenario demonstrates how LKA can be ambitious in their policy decisions where 70% of electricity generated in 2030 will be from clean sources, i.e., 50% from renewables and 20% from natural gas.

Despite national policies being designed for 2030, the assumptions are extended beyond 2030 until 2050, to develop a long-term overview and analyze mid-century decarbonization perspectives.

3. Climate, Land-Use, Energy, and Water Systems (CLEWs) modeling for Sri Lanka

3.1. An overview of the CLEWs framework

CLEWs is a methodology for integrated assessment of resource system interlinkages among energy, land-use, and water systems as well as climate via a qualitative approach. The CLEWs model was developed and applied first in the case of Mauritius in 2012 (Howells et al., 2013). Since then, CLEWs have been applied to different country contexts, the latest being the case of Ethiopia (Tesfaye et al., 2021).

The CLEWs framework is built within the Open-Source Energy Modelling System (OSeMOSYS) (Howells et al., 2011), which is a demand-driven bottom-up model used for long-term energy planning. The objective function of the model is to minimize the total discounted costs of configuring the technologies to meet the exogenously defined demands over the entire modeling horizon. The technologies (e.g. power stations) are described using their techno-economic characteristics (e.g. performance of technology, availability, capacity, and costs) and pose constraints to the objective function. Complete documentation of the OSeMOSYS model is given in (KTH dESA, 2018a).

To develop a CLEWs model in OSeMOSYS, a simplified national reference resource to service system (RRSS) diagram was drawn. This helps to identify all the relevant technologies and resource flows that will be involved in the analysis. Figure 2 shows an example of RRSS from the Ethiopian case study (Tesfaye et al., 2021). As shown in the RRSS, the model is generally composed of four tiers forming a value chain for different commodities (e.g. electricity, water, food) from primary resources supply, generation/production technologies, transmission/distribution technologies to final demands inclusive of inter-sectoral demands (e.g. fuel demand for crop production as shown in dotted lines in figure 2). The model computes the acquisition and operation of assets in a way that converts natural resources into commodities that meet the specified demand in a least-cost mix of technologies subjected to technical and economic constraints. Further details on CLEWs are given in (Arderne, 2016; KTH dESA, 2018b; Moksnes, 2016).

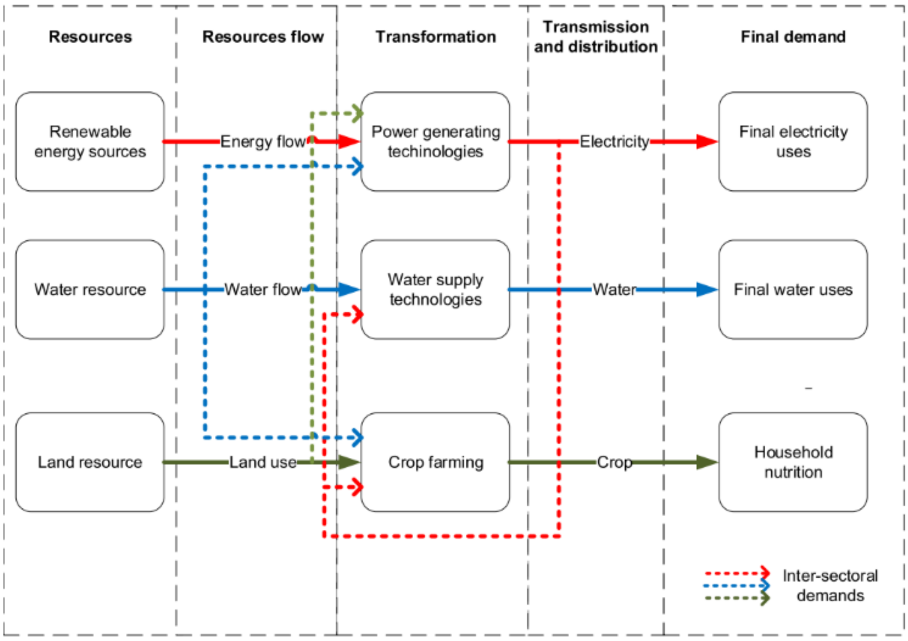

Figure 2: An example RRSS.

3.2. Data collection and model setup

Data were collected using several sources and public documents. Energy data are adopted from Sri Lanka Energy Balance, Long-Term Generation, and Expansion Plans and statistical digests of CEB, annual reports of CEYPETCO reports. The data include the capacity, demand, and techno-economic data of technologies (IEA, 2020). The electricity demand in particular was considered for three seasons; Wet, Dry, and High Wind, and a day is considered over three time slices as the CEB; Peak, day-peak, and off-peak. The demand forecast for electricity follows the CEB projections. It was assumed that the power sector expansion is expected to have Natural Gas from 2024 onwards in addition to renewables (CEB, 2021b; PUCSL, 2017).

The percentage of land use by different land-use categories is considered in the model with certain constraints (i.e. land area used by water bodies remains the same whereas minimum forest coverage is above 30%) (Sri Lanka UN-REDD Programme, 2017). Grasslands and shrublands remain open for agricultural expansions, human settlements, and renewable energy development purposes (Department of Land Use Policy Planning, 2014). Agriculture land-use and land-use changes over the modeling period are considered with demand forecasts for major crops (i.e. paddy, tea, rubber, and coconut) (CBSL, 2020; Department of Census and Statistics, 2022). The model includes import and export constraints for paddy and a few other crops reflecting the self-sufficiency principle (Ministry of Agriculture, 2021).

Within the CLEWs framework, the scenarios and their narratives are translated into data inputs and or constraints. For example, assumptions on the choice of technologies and the evolution of final commodity demands over the time horizon are exogenous inputs. Additionally, the narratives such as 50% of electricity being generated from renewable sources in 2050, are modeled using additional constraints within CLEWs. The modeling period is chosen from the year 2020 to 2050. The historic year (2020) outputs were utilized to calibrate the model parameters.

4. Results and Discussion

The CLEWS modeling approach allowed the exploration of several result matrices across energy, land-use, agriculture, and water supply sectors in Sri Lanka. The following results exclude the water supply sector as it was not scoped into this exercise.

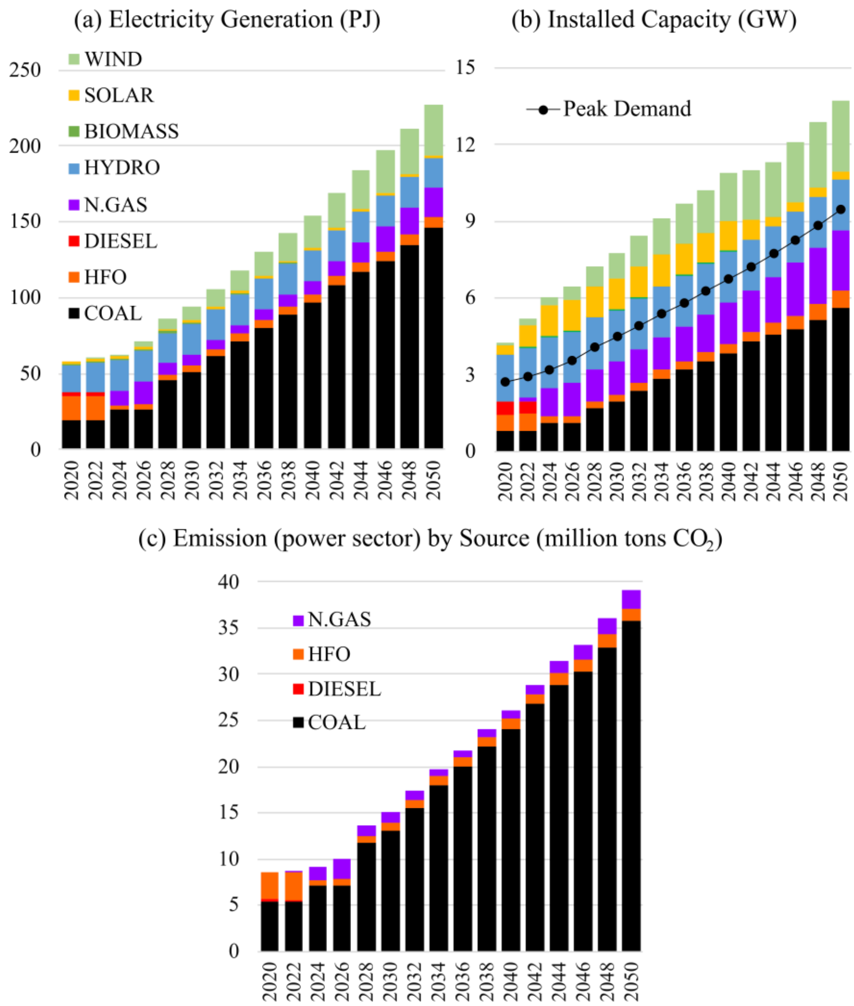

Figure 3: a) Electrical energy generation by source, b) the corresponding installed capacity, and c) the CO2 emissions from the power sector by fuel source.

The BAU Scenario results on a) electrical energy generation, b) the corresponding installed capacity, and c) the CO2 emissions from the power sector by fuel source are shown in Figure 3. In the BAU scenario, the electricity generation is dominated by coal where the contribution from renewable energy sources is less than 40% (in 2050). The emissions increased 4 times over the study period.

For the same scenario (BAU), figure 4 shows a) the total land use across different categories, and b) cultivated area by crop in the agricultural sector. The forest cover in Sri Lanka remains the same, about 30% of the total land posing a significant constraint on land use for development activities and agriculture. Since there is an increase in the demand for crops, most of the grassland and shrublands are expected to be converted to agricultural land. As a key crop, rice dominates the land used for agriculture. In alignment with the policy priority for self-sufficiency in rice production, land use for rice cultivation has an increasing trend. There are no significant changes in the land area used for tea, rubber, and coconut.

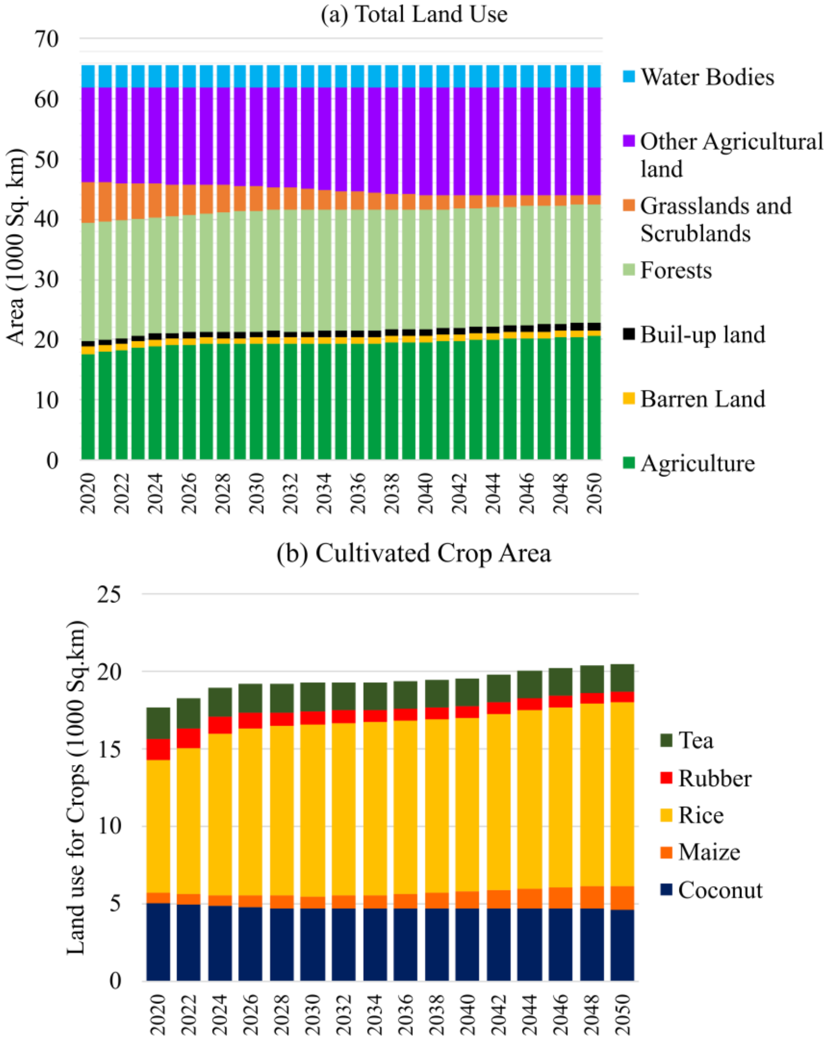

Figure 4: a) the total land use across different categories, and b) cultivated area by crop in the agricultural sector.

The scenarios on Existing Policy and Perceived Policy showcase the expected improvement in fuel diversity and security of supply. Figure 5 provides a comparison of electricity generation across the three scenarios. A significant diversion in the modeling results, in comparison to the BAU Scenario, is also noticeable. Significant renewable energy (predominantly solar and wind power plants) generation under the Existing Policy scenario is expected to reduce the use of coal. Perceived Policy direction further eliminates coal due to the policy that favors the addition of more natural gas power stations in addition to the conversion of existing oil power stations to run on natural gas.

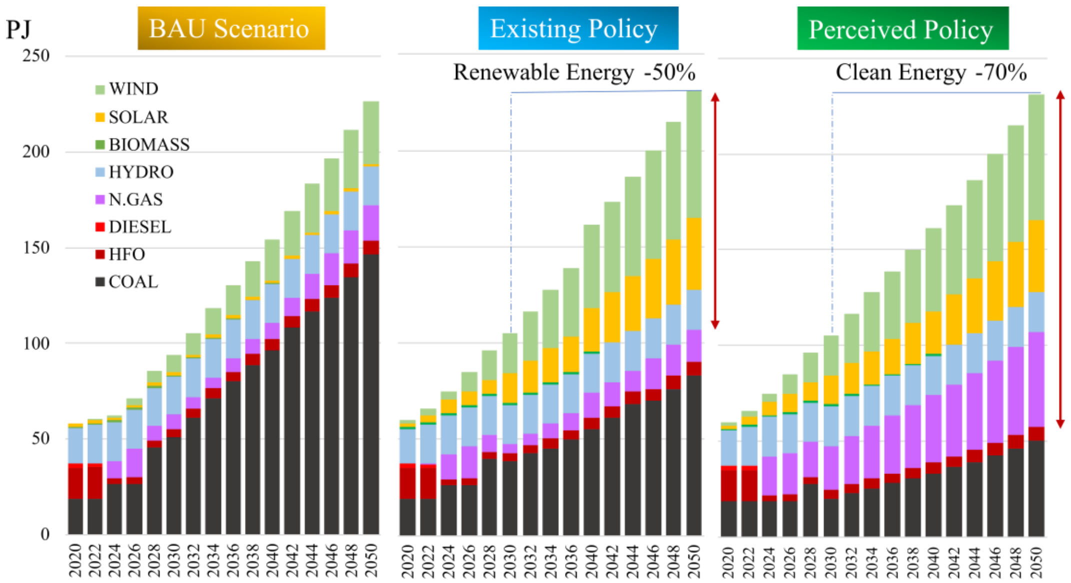

Figure 5: Annual electricity generation (Peta Joules) across the three scenarios.

The total installed capacities under the Existing and Perceived Policy Scenarios will be nearly doubled compared to the BAU Scenario. This is a result of renewable energy technologies, particularly wind and solar PV having lower capacity factors, which results in a large installed capacity compared to thermal units which can operate at any time of the day, throughout the year. In BAU scenario thermal plants have higher capacity factors, resulting in much less installed capacity to provide the same output of electrical energy. Figure 6 illustrates a comparison of installed capacity across different scenarios.

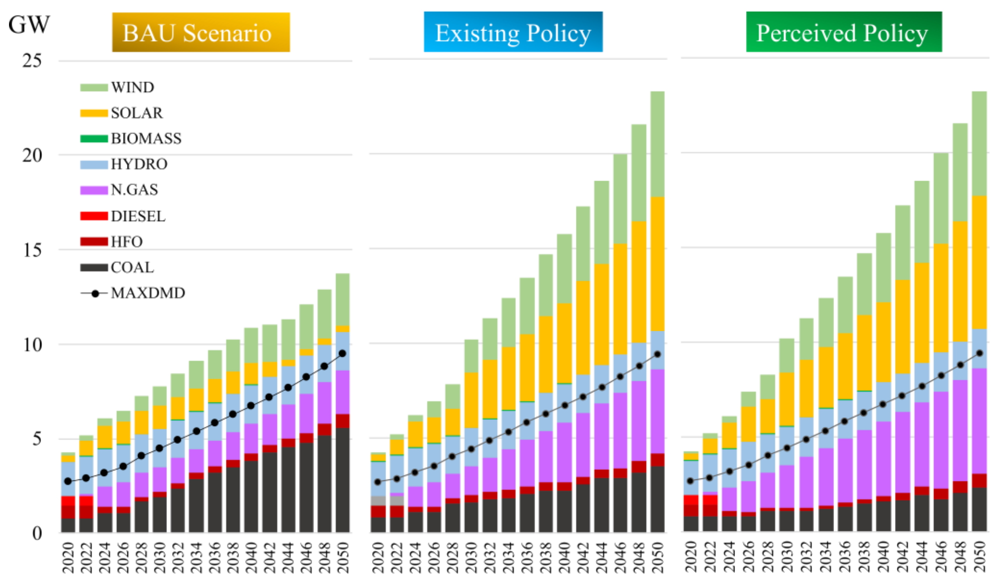

Figure 6: Installed electricity generation capacity for the three scenarios.

A minimum of 2.5% reserve margin requirement above peak demand was maintained through a balance of firm capacity power plants in all three scenarios. Particularly, an increase in natural gas power plant capacity is observed as the principal baseload generation under the Perceived Policy scenario.

It is important to note that, with the integration of high intermittent renewable energy capacities, the necessity to evaluate the requirement of grid-supporting/balancing technologies becomes more pivotal. These include energy storage such as pumped storage and battery storage efficient renewable energy forecasting and controlling systems, transmission infrastructure, and smart grids with inertia support (to name a few). The requirement of these grid-supporting technologies and the corresponding cost associated with it is not included in this modeling effort.

Irrespective of the cost associated with grid-supporting technologies, it is observed that the cost of electricity generation in the Existing Policy and Perceived Policy scenarios, did not deviate significantly from BAU Scenario (Figure 7). The BAU Scenario would cost ~28.5 USD billion covering the 2020-2050 period. The costs are expected to increase by +1% for Existing Policy and +4% for Perceived Policy scenarios in comparison to the BAU. The overall calculation in all scenarios also excludes legacy costs of existing infrastructure.

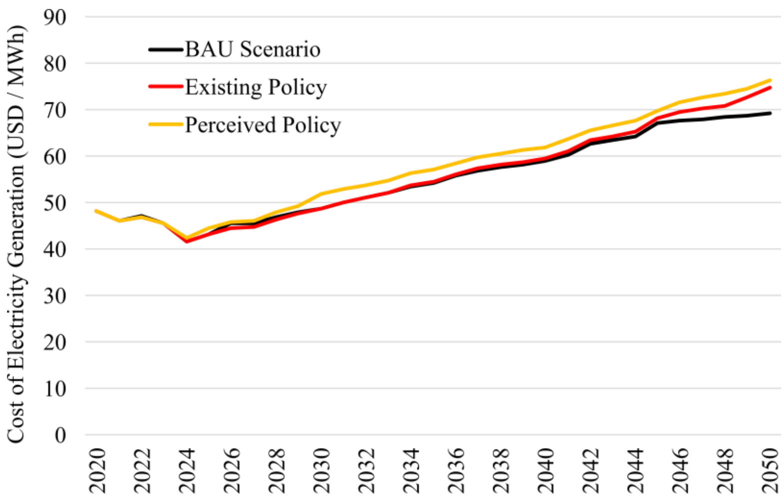

Figure 7: Cost of electricity generation for the three scenarios.

This minor increase in overall scenario cost is because even though the operational cost is decreased with the introduction of renewable energy technologies, the additional investment cost is required to incorporate renewable energy technologies in addition to the firm capacity power plants. Furthermore, even with the global trend of cost reduction of renewable energy technologies, that advantage may not be available in developing countries like Sri Lanka considering the facts such as economies of scale and current economic and financial constraints. However, during the horizon of 2020-2050, the costs are expected to decrease further with technological enhancements and economies of scale.

The expected GHG emission of the energy sector (Figure 8) is expected to increase fourfold (~8Mt in 2020 to ~38Mt in 2050) in the BAU scenario. This can be significantly reduced by 32% in the Existing and by 44% in the Perceived Policy scenarios compared to the BAU scenario. The Existing and Perceived Policy scenarios showed a significant potential to reduce GHG emissions above the requirement of the NDC commitment by 25% (20% conditional and 5% unconditional) during the period from 2021-2030 if the low-carbon power plants are implemented on time. The marginal abatement cost of the same two scenarios appears to be in the range of fewer than 5 USD/tCO2e which will be attractive for investments in green /clean technologies.

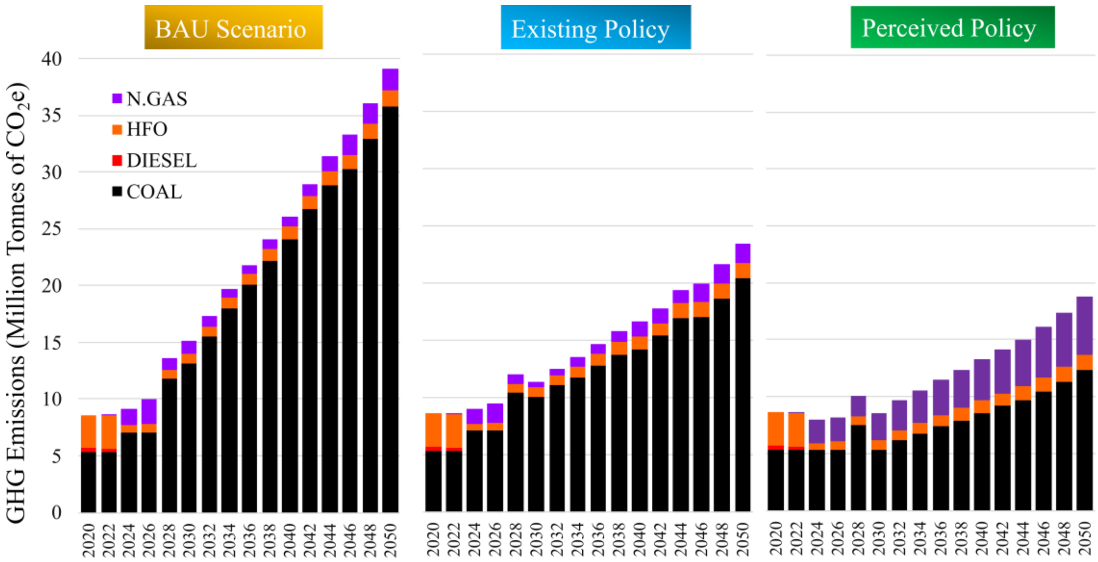

Figure 8: GHG emissions in comparison for the three scenarios studied.

The required land for renewable energy is as low as 7.6% as a fraction of available grass and scrub lands. This is not significant unless there are regional land allocation limitations and competing land use priorities for agriculture and economic development activities, some of which already make it difficult to source suitable lands for renewable energy development activities. This issue is to be further analyzed in the next stage of the study.

5. Conclusion

Renewables and Natural Gas as an alternative to coal shall contribute to reducing country GHG emissions significantly in the power sector. Current policy directions in this regard will have major environmental benefits. Furthermore, this will increase the diversity of primary energy sources as well as the expected economic benefits due to the lower requirement for fossil fuel import. However, considering the economic status of the country, external climate finance support may be required for investment in more clean energy technologies which heavily contribute to the mitigation of climate change impacts in the country.

However, the study has the limitation of not considering grid integration and system stability and associated costs. It is understood that the integration of intermittent renewable energy is to be supported with some additional upgrades to the existing transmission networks and associated other interventions that require additional investments. The study needs to re-evaluate the technical limitations of the above results with power system studies, bringing additional technical requirements including costing and comparison of economic output.

Even though the study indicates that the grass/scrub lands alone can cater to renewable energy developments, the need for land-use planning is needed to avoid potential conflicts for agriculture, forestry, and renewable energy developments. The ongoing regional/local level analysis with precise data use is expected to confirm the results.

A planned model upgrade is to cover the aspects of both mature and unproven energy storage (pumped hydropower plants, and new energy storage types such as battery energy storage) types. Integration of energy storage is expected to enhance power system stability as well and the use of energy storage can further lower the demand for reserve margin capacities. Regional land-use availability for agriculture and RE developments will be expected to further assure policy above recommendations.

Furthermore, given the existing crisis in Sri Lanka, the NDCs and national policies may require a thorough revision. In addition to CLEWs, there needs to be soft linkages with macroeconomic models to understand the dynamics of the Sri Lankan economy, primarily how future investments are available for development activities under the conditions of the International Monetary Fund.

Acknowledgments
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EFFICACY OF GREEN BUILDING RATING SYSTEMS TO PROTECT THE BIO-DIVERSITY OF SRI LANKA

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Abstract: Green building rating systems (GBRS) are acquiring growing popularity in international and local construction industries due to the increasing adverse impacts on the natural environment by buildings. GBRS is considered an important tool for minimizing threats to natural environments using fewer natural resources for building construction and operation without sacrificing user comforts. Therefore, GBRS are vital to be used in a country like Sri Lanka as it is a place rich in Biodiversity and is one of the 36 biodiversity hotspots in the world. Although the GBRS is internationally recognized as an effective tool for environmental protection, its real efficacy specifically on biodiversity protection has not been explored yet. Thus, mixed-method research was carried out to evaluate the efficacy of biodiversity protection through GBRS. Initially, LEED, GREENSLR, and BLUE GREEN SL rating systems were explored to find the biodiversity protective criteria in their evaluation schemes. Due to a gap available in the literature on how to figure out BD protective criteria and points in GBRS, the_‘ “targets of post-2020 global biodiversity framework (P-2020 GBDFT)’ ” were taken as a reference material and mapped with GBRS criteria to highlight biodiversity protective criteria. Consequently, 02 high-rated green buildings, rated by the above-mentioned GBRS were selected as case studies and explored the contribution of biodiversity protective criteria for the rating they have obtained. The results revealed all the considered GBRS contain 65%-76% of biodiversity protective points. However, all the selected case studies have omitted 07 to 11 biodiversity protective criteria containing 08% to 25% biodiversity protective points, and still have managed to achieve Gold to Platinum ratings using other criteria. According to the present study, it is revealed that GBRS are inefficient in biodiversity protection as it is not a must to obtain a high green rating though there is an impact on biodiversity. Therefore, the study recommends improving GBRS by adding separate biodiversity protective aspects, to highlight biodiversity protective features and to increase biodiversity protective prerequisites in GBRS in protecting biodiversity.

Keywords: Biodiversity; Green Building Rating Systems; LEED; GREENSLR; BLUE GREEN SL

1. Introduction

1.1 Background

An Island located in the Indian Ocean on the equatorial belt, Sri Lanka is rich in the natural environment. Due to its wealth of a variety of ecosystems with rich biodiversity (BD), it is named one of 36 BD hot spots in the world (IUCN, 2013). The survival of this natural life is sensitive to their environment and depends upon these extraordinary conditions. Therefore, any minuscule change to the environmental conditions will have a considerable impact on biodiversity. Anthropogenic activities, direct or indirect, involve different ways and have many influences on ecosystem composition, especially through species extinction (Sponsel, 2013). Also, the BD hotspots are irreplaceable assets and play a key role in keeping the earth's life. Due to rapid developments, the building density is increased causing effects on the natural environment degradation. "Floor area in the buildings sector worldwide is expected to increase 75% between 2020 and 2050 (Energy Agency, 2021).

So, the green building rating systems (GBRS) are introduced as one of the environmental protective tools to minimize the adverse effects of the buildings on the environment. The most popular GBRSs in Sri Lanka are GREEN^{SLR} by the Green Building Council of Sri Lanka (GBCSL), Blue Green Building Sri Lanka by the Urban Development Authority (UDA), and LEEDS (Leadership in Energy and Environmental Design) by US Green Building Council. Sri Lanka has only two locally introduced GBRSs, which are GREEN^{SLR} and Blue-Green Building Sri Lanka.

In Sri Lanka, many green-rated buildings exist. A number of them are located near highly sensitive ecosystems. However, the practical efficacy of protecting BD by GBRS has not been specifically studied in the international or Local context. Therefore, it is questionable whether the buildings elected as high-rated through green rating assessments are addressing the BD issues and their protection.

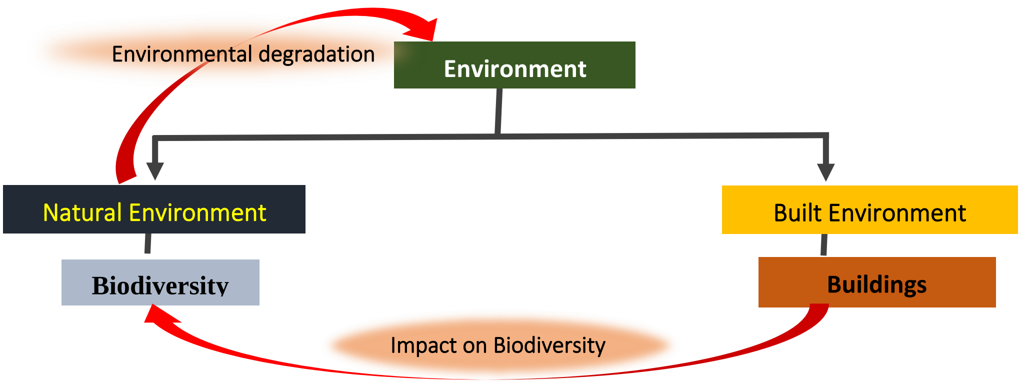


Figure 1: Concept Map- Natural Environment and Built Environment.

1.2 Aim and Objectives,

The overall aim of this study is to evaluate the efficiency of green building rating systems on biodiversity protection in Sri Lanka. The study serves two main purposes and three objectives to achieve the overall aim as follows,

The first purpose, comparing the efficacy of different GBRSs in protecting biodiversity, aligns with the first objective of identifying the impacts of buildings on biodiversity. This helps establish the context for evaluating the effectiveness of GBRS in addressing these impacts.

The second purpose, appraising the efficacy of biodiversity protection in green accreditations of buildings, directly corresponds to the third objective of assessing the efficiency of GBRS in BD protection through case studies. This involves examining real-world examples to validate the effectiveness of the rating systems in practice.

Objectives are,

1. To identify the impacts of buildings on biodiversity.

Understanding how the construction and functioning of buildings influence local ecosystems, species populations, and overall ecological health.

2. To find and compare the BD protective criteria in local and international GBRSs.

Identify Relevant Rating Systems and go through the documentation, guidelines, and criteria, which look for sections or categories that address biodiversity, and ecology in each GBRS.

3. To assess the efficiency of GBRS in BD protection concerning green-rated buildings in Sri Lanka (Case Studies) Assessing the efficiency of green building rating systems (GBRS) in biodiversity (BD) with studying and analysis of case study data

1.3Significance of The Study

Accordingly, the study will help to identify the loopholes in green rating systems in terms of biodiversity protection. Therefore, the existing green rating systems will be able to strengthen themselves to reduce negative bio-diversity impacts by buildings. Further, the study will help to improve BD aspects of existing, green-rated buildings by strengthening the operational guidelines for building. Finally, the overall study will be a guide to improve the green rating systems to become specific to protect the Sri Lankan natural environment by providing directions to building professionals such as Engineers, architects, and builders.

2. Literature Review

2.1 The Biodiversity of Sri Lanka.

Biodiversity (BD) is "the variety and variability of living organisms broadly including a wide diversity of plant and animal species, communities, and ecosystems" (USAID, 2003).

According to (Faa and Forest, 2012) Sri Lanka is rich with an extremely high level of biological diversity in its ecosystem within a small island with a land area of 65,610 km2. Also stated is that Sri Lanka has the place of richest species diversity per unit area in the Asian region, and mostly these species are amphibians, reptiles, fish, mammals, and flowering plants. Also "as an oceanic island, Sri Lanka has a high percentage of endemic species that have evolved because of isolation, but they are particularly vulnerable" (Baldwin, 1991)

The island hosts several 'point endemic species and even monotypic endemic genera. However, this irreplaceable biodiversity is now under severe threat because of extensive anthropogenic land use changes that began over two centuries ago, under colonial rule and continue to this present date.

2.2 Natural Environment and Built Environment.

The surrounding environment can be named to be comprised of two components, the built environment and the natural environment. The built environment and natural environment have considerable interrelationships with each other. "All environmental systems are interrelated. Extension of the built environment to meet the needs of the population growth puts pressure on the natural environment by using more land, water, and energy resources, as well as producing waste and emissions through consumption activities" (Australian Government, 2020).

2.3 Impact of Built Environment on Biodiversity

Accordingly, through the literature, the following has been revealed as an impact on the natural environment and a case for the loss of biodiversity by building.

Excavation and soil compaction on construction sites - can reduce the soil's infiltration capacity, and evapotranspiration, and change the chemical and physical structure of the soil, impacting the ecosystem's capacity to perform natural biophysical processes and topsoil biodiversity degradation. (Salata and Thompson Couch, 2022). The buildings have continually contributed to a higher global concentration of GHGs in the atmosphere (Bendewald and Brew, 2010). The buildings had interrupted the flow of air to the soil, effectively producing a closed, warm, polluted canopy of air overhead" (Mohan K. Wali et al., 2010). Draining of wetlands; construction of houses, resorts, and roads; and filling along the shoreline are the main urban activities that threaten (Mohan K. Wali et al., 2010).

Develop health problems from long-term exposure to high levels of dust, and noise on fauna around the construction sites- Can cause hypertension, high stress levels, tinnitus, hearing loss, sleep disturbances, and other harmful effects induced hearing loss is irreversible damage to the ears caused by exposure to high levels of noise. Breathing can cause diseases like lung cancer, asthma, Chronic Obstructive Pulmonary Disease, and silicosis. (National Water Supply and Drainage Board, 2016)

"The construction industry has a significant irreversible impact on the environment across a broad spectrum of its activities during the off-site, on-site, and operational activities, which alter ecological integrity" (Ametepey and Ansah, 2015). The built environment has highly contributed to altering the natural landscape and fragmentation of ecosystems. Moreover, unsustainable is the main driver of the loss of biodiversity and degradation of the ecosystem (Zari, 2015). The amount of impervious surface, and soil compaction during construction directly affects to hydrological cycle by reducing permeability, increasing flood, decrease of watershed of rivers, lakes, estuaries, and streams. (Mukrimaa *et al.*, 2016)

During their construction, occupancy, renovation, repurposing, and demolition, buildings use energy, water, and raw materials, generate waste, and emit potentially harmful atmospheric emissions (Atta and Bakhoum, 2023). Building effects on biodiversity have been explained as vegetation removal, loss of edaphic soil, potential soil erosion, interception of water bodies, and interference with the ecosystems (Ametepey and Ansah, 2015). Since Sri Lanka has a high biodiversity and a vital natural environment, the country has taken many remedial actions and sustainable management procedures to reduce the degradation of the natural environment. Since the British colonial era, the Island has implemented more than 90 environment-related regulations that have been enacted over the span of 100 years. Also, there are Environmental Assessments, Policies, Rules & Regulations, Laws, and GBRS to protect the natural environment. Further, the country has adhered to Environment-related International Conventions, Protocols, Treaties, Tools, and guidelines in terms of natural environment and BD protection (JICA, 2012).

2.4 The Convention on Biological Diversity

The Convention on Biological Diversity (CBD) was established in the year 1992 and recognized by international law as an essential part of the development process. (David Cooper and Noonan-Mooney, 2013). Further, The CBD is the international legal instrument for the conservation of biological diversity (David Cooper and Noonan-Mooney, 2013). In 2022, parties to the UN Convention on Biological Diversity (CBD) determined the post-2020 global biodiversity framework (P-2020 GBDFT) and it has established to protect the BD and living in harmony with nature; further, it contributes to the objectives of the Convention on Biological Diversity, its Protocols, and other biodiversity-related multilateral agreements (Secretariat of the United Nations Convention on Biological Diversity, 2021). UN Sustainable Development Goals (SDG) is the best example for this matter. "The Post-2020 Global Biodiversity Framework targets (P-2020 GBDFT) are expected to make significant contributions to the achievement of several Sustainable Development Goals (SDGs), (Oberle, 2022). There are 08 action targets described under the reducing threats to BD.

2.5 Green Building Rating Systems (GBRS)

"A Green Building Rating System (GBRS) is a set of guidelines, criteria, and standards to evaluate and assess the sustainability and environmental performance of buildings"

Different GBRS are in practice around the world and in Sri Lanka. "The First Green building rating system BREEAM, Building Research Establishment's Environmental Assessment Method was introduced to the world by the United Kingdom in 1997, and subsequently United States Green Building Council (USGBC) introduced LEED, the world-famous Leadership in Environmental and Energy Design green building rating tool in year 2000 (Reed, Krajinovic-Bilos and Reed, 2017).

Common GBRS is being practiced in Sri Lanka.

1. GREENSLR by Green Building Council of Sri Lanka (GBCSL)
2. Blue Green Building Sri Lanka by Urban Development Authority (UDA)
3. Leadership in Energy and Environmental Design (LEED) by U.S Green Building Council

2.6 Green Building Rating System Structure and Point Score Structure

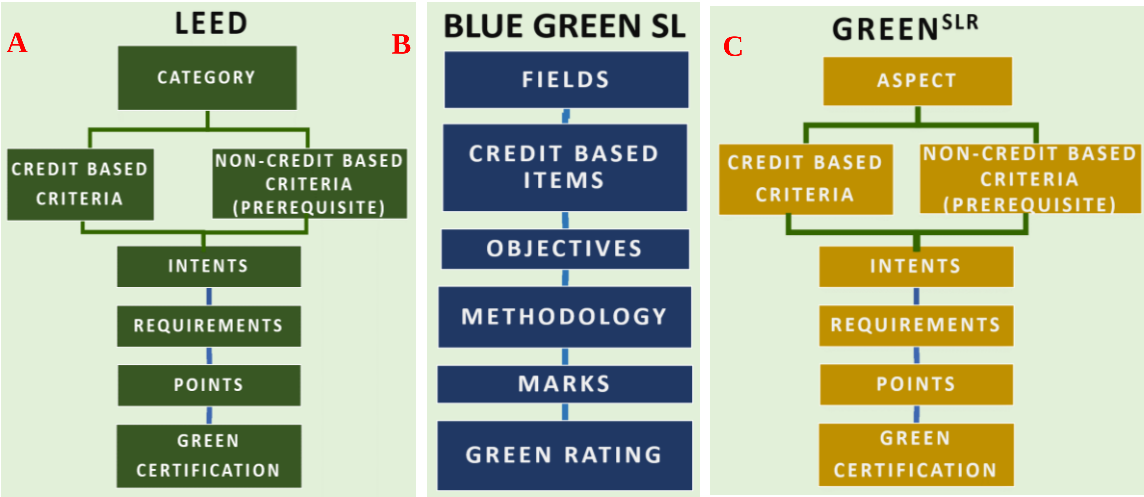


Figure 2.1 Green Building Rating System structure of A) LEED, B) BLUE GREEN SL and C) GREEN^{SLR}.

Table 2.1 Point Score structure of each GBRS

GBRS	**Green Certification**	**Required points range**
LEED	LEED-certified	40-49 Point
	LEED Silver	50-59 Points
	LEED Gold	60-69 Point
	LEED Platinum	70 Points ≤
Blue Green SL	GREEN Certified	40-49 Point
	GREEN Silver	50-59 Points
	GREEN Gold	60-69 Point
	GREEN Platinum	70 Points ≤
GREEN^{SLR}	GREEN^{SLR} certified	40-49 Point
	GREEN^{SLR} Silver	50-59 Points
	GREEN^{SLR} Gold	60-69 Point
	GREEN^{SLR} Platinum	70 Points ≤

3. Research Methodology

The research was led with mixed methods to approach objectives. A desk study was carried out in terms of seeking data to achieve objective 01. The second objective contains three (03) parts. Identify current GBRS in Sri Lanka, Find BD protective criteria in GBRS, and Compare BD protective criteria among GBRS. The aspects and criteria of selected GBRS were mapped with “The targets of post-2020 global biodiversity framework (P-2020 GBDFT) in Conversion of Biological Diversity to identifying BD protective criteria. Then, the GBRS criteria that comply with P-2020 GBDFT were identified as BD protective criteria and each GBRS was compared using their inbuilt point scales with results translated into graphs.

3.1Method of Finding BD Protective Criteria in GBRS

Table 3.1: Sample table of finding BD protective criteria of GBRS

LEED		BLUE GREEN SL		GREEN^{SLR}	
Water Efficiency (WE)		Water Efficiency (WE)		Water Efficiency (WE)	
Criteria	Points	Criteria	Points	Criteria	Points
WE 1-Outdoor water use reduction	PR	WE 1-Rain water harvesting	02	WE 1-Eliminate potable water consumption for irrigation and landscape	PR
WE 2-Indoor water use reduction	PR	WE 2-Waste water recycling & efficient use	04	WE 2-Use of alternative water sources	01
WE 3-Building-level water metering	PR	WE 3-Water metering & water leaks identification system	02	WE 3-Use of water saving performances	01
WE 4-Outdoor water use reduction	02	WE 4-Water efficacy tools equipment	02	WE 4-Indoor water use reduction	04
WE 5-Indoor water use reduction	07			WE 5-Water efficacy in air conditioning system	01
WE 6-Cooling tower water use	02			WE 6-Innovative wastewater technologies	05
WE 7-Water metering	01			WE 7-Innovative water transmission	01
				WE 8-Ground water recharge, if ground water sources are tapped	01
Total points to protect BD	**12/12 (100%)**	**Total points to protect BD**	**6/10 60%**	**Total points to protect BD**	**13/14 92%**

Definitions of the table content

01. Name of the GBRS
02. Name of the "Aspect" taken into consideration under the GBRS
03. The list of "Criteria" comes under the selected aspect.
04. Name of the Individual criteria mapped with the; **targets of the post-2020 global biodiversity framework (P2020 GBDFT)**. If the "intent" of criteria matches the section and **reduces the threats to biodiversity,**
    those criteria are named "Biodiversity (BD) protective criteria" and are marked in green color.
    (A sample mapping of Individual criteria with P-2020 GBDFT is given below in Table 3.2)
05. Points allocated for each criterion under the GBRS.
06. PR: Pre-requisite criteria of GBRS
07. The percentage of points that are allocated for BD protective criteria.

Table 3.2: A sample mapping of Individual criteria with P-2020 GBDFT

Criteria	Intent	Relevant post-2020 global biodiversity framework Target (P2020GBFT)
WE1: Eliminate potable water consumption for irrigation and landscape	Landscape with indigenous plants to reduce or eliminate irrigation requirement, no circumstances of invasive plants and non-indigenous plants	**Target 2:** Ensure that at least 20 percent of degraded freshwater, marine, and terrestrial ecosystems are under restoration, ensuring connectivity among them and focusing on priority ecosystems.

The third objective was achieved by case study research method with a convenient sample of two buildings (Table 1)

Table 3.3. Details of the case study buildings

Name of the building		Function	Number of floors and Area	Green rating and received a year
Case study 01	Iceland Building Colombo 03	Office	8 floors & 6800m^2	• LEED-PLATINUM 2017 • GREEN^{SLR}- GOLD 2017
Case study 02	National Environmental Secretary Building Battaramulla	Office	10 floors & 8500m^2	• BLUE GREEN SRI LANKA- GOLD 2017 • GREEN^{SLR}-GOLD 2017

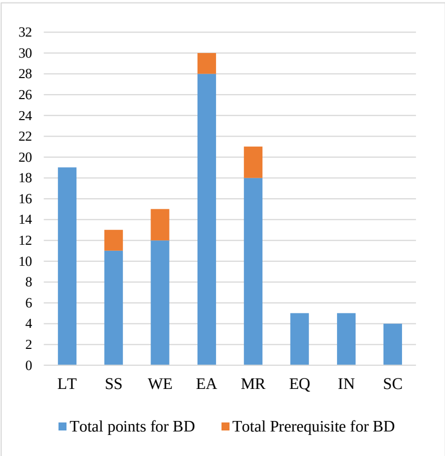
First, the points obtained by each building through relevant GBRS were examined. Given that, the points scored by each case study building for each green aspect were calculated. The results were analyzed using graphs to find the proportion of BD protective green aspects that were involved in achieving the relevant green rating of the particular case study.

4. Results and Discussion

The following discussion explores the BD features in each GDBRS through their inbuilt marking scheme concerning P-2020 GBDFT. The technical terms discussed in the methodology chapter will be used for the analysis and the discussion. A separate table is used to discuss each aspect of the three (03) GBRS. After the table, identified BD protective criteria under the particular aspect of GBRS will be discussed.

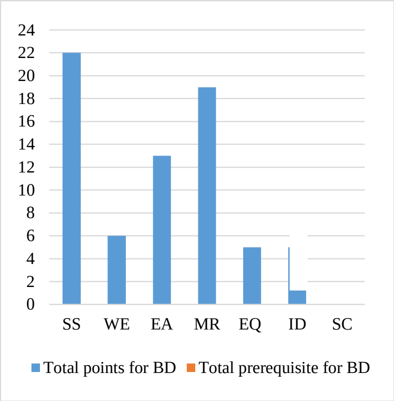
4.1 Analysis of GBRS on BD Protection

The amount of BD protective points and BD protective prerequisite criteria (PC) in each GBRS is shown below: A separate column is shown in each table to discuss each eight aspects of the three (03) GBRS. Eight aspects are Location and Transportation- LT, Management- MN, Sustainable Sites- SS, Water Efficiency, Energy and Atmosphere, Material & Resources, Indoor Environmental Quality, Innovation-IN, and social-cultural awareness.



BD protective points:
LEED : 69%
BLUE GREEN SL : 65%
GREEN^{SLR} : 76%

Figure4.1 BD protective criteria of LEED with reference to P2020 GBFT.



BD protective prerequisite criteria:
LEED : 10/15 = 66% PC
BLUE GREEN SL : 00 = 00% PC
GREEN^{SLR} : 04/13 = 30% PC

Figure4.2 BD protective criteria of BLUE GREEN SL with reference to P2020 GBFT.

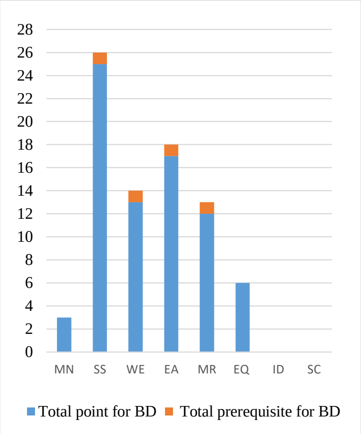


Figure 4.3 BD protective criteria of GREEN^{SLR} with reference to the P2020 GBFT.

Thus, all GBRS has shown almost similar contributions to the protection of BD.
LEED has the highest amount of PCs. BLUE GREEN SL has zero in PC for BD protection. GREEN^{SLR} has the highest number of criteria-based BD protective points (76%) and has given more contribution to BD protection than other 02 GBRS.

4.2 Case Study Summary

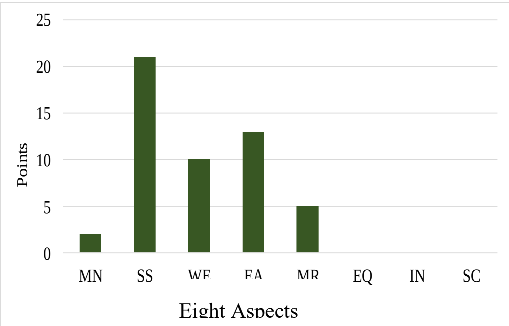
4.2.1 Case Study 01

Name of the building; Iceland Business Center (IBC) at Colombo 03
Owned by; the International Construction Consortium (ICC).
The building was commissioned in; 2017.
Awarded Green Building Ratings; LEED PLATINUM certification
GREENSLR GOLD certification

Figure 4.2.1 The IBC building.

A). GREEN^{SLR} - Certification of IBC building

GREEN^{SLR} has a 0 to 100-point range to achieve respective green certifications. Figure 4.2.2 illustrates the point scored by the IBC building for all its criteria under the eight aspects regarding BD protection by GREEN^{SLR}.



- The IBC building scored 65% of point to obtain the GREEN^{SLR} GOLD certification
- Scored 51% of points for BD protective criteria.
- GREEN^{SLR} contains 76% of GB protective points according to original Analysis in section 3
- Thus, IBC building have missed 25% GB protective points

Figure 4.2.2 –BD protective Point comparison of IBC building - GREEN^{SLR}.

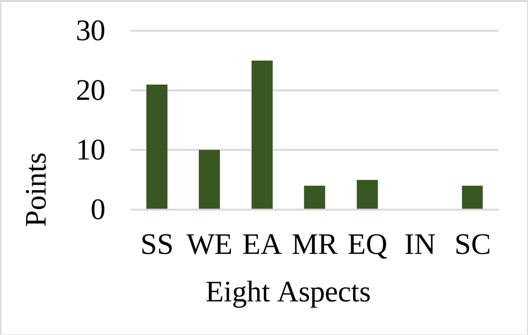
Following BD protective criteria under the eight aspects are not followed by IBC building to obtain GREENSLR GOLD certification;

: Wastewater Technologies (SS6)
: Optimize Energy Performance (EA4)
: Building Reuse (MR2)
: Certified timber (MR8)
: Low Emitting Materials (EQ6)
: Indoor Chemical & Pollutant Source Control (EQ7)
: Controllability of systems (EQ8)

Therefore, IBC building has managed to achieve the comparatively higher award of Gold certification by GREENSLR, although not having fully achieved 07 criteria containing 25% GB protective points.

B). LEED- Certification of IBC Building

LEED Has a 0 to 110 points range to achieve respective green certifications. Figure 4.2.3 illustrates the point scored by the IBC building for all its criteria under the eight aspects regarding BD protection by LEED.



- The IBC building scored 76% of point to obtain the LEED PLATINUM certification
- Managed to score 61% of points for BD protective criteria.
- LEED originally contains 69 % of GB protective points according to the section 3
- Thus IBC building have missed only 08 % GB protective points

Figure 4.2.3 BD protective Point comparison of IBC building- LEED ratings.

Following BD protective criteria under the eight aspects are not achieved by IBC building to obtain LEED Platinum certification;

: Brownfield Redevelopment (SS 4)
: Site Development (SS 6)
: Storm water Design (SS 7)
: Light Pollution Reduction (SS 9)
: Optimize Energy Performance (EA 4)
: Building Reuse (MR 2)
: Certified Wood (MR 8)
: Construction IAQ Mgmt. Plan- (EQ 5)
: Low-Emitting Materials (EQ 6)

Therefore, IBC building has managed to achieve the highest award of Platinum certification by LEED, although without having achieved 09 criteria containing 08% GB protective points

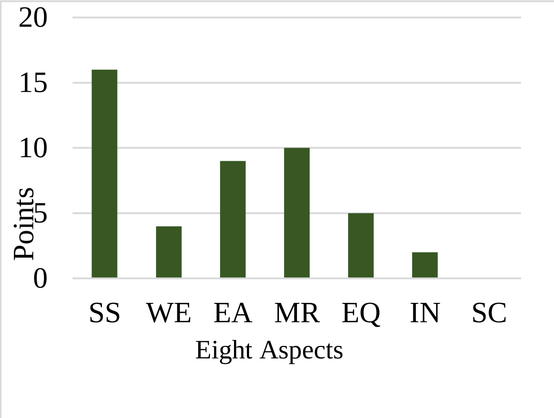
4.2.2 Case Study 02

- Name of the building; National Environmental Secretariat (NES) Building
- Owned by; the Ministry of Environment and Mahaweli Development of Sri Lanka
- The building was commissioned in; 2017
- Awarded Green Building Ratings ; BLUE GREEN SRI LANKA GOLD ; GREEN^{SLR} GOLD certification

Figure 4.2.4: Front views of the NES building.

A) Blue Green SL Certification of NES Building

Figure 4.2.4 illustrates the point scored by NES building for all its criteria under the eight aspects regarding BD protection by Blue Green SL



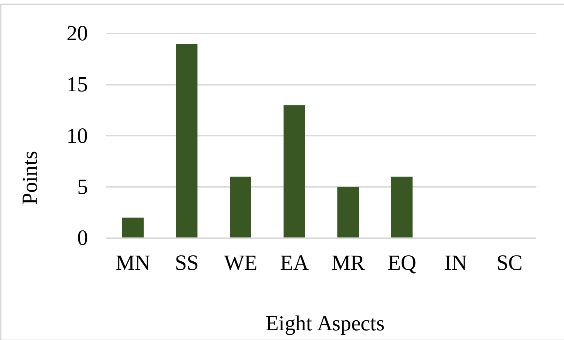
- The NES building has scored 46% BD protective points.
- It has scored 71% points to obtain BLUE GREEN SL Gold certification
- The BLUE GREEN SL originally contains 65% of BD protective points analysis done in section 3

Figure 4.2.5. BD protective point comparison of NES building - BLUE GREEN SL.

Following BD protective criteria have not been achieved by the NES.
: Site selection (SS 1)
: Abandoned (brownfield) site redevelopment (SS 2)
: Development density & community coordination (SS 3)
: Wastewater recycling & efficient use (WE 2)
: Renewable energy (EE 3)
: Material containing recycled substance. (MR 2)
: Re-use of an existing building (MR 3)
: Construction waste management (MR 7)
: Refrigerant and cleaning agents (MR 8)
Therefore, NES has omitted 19% GB protective points with 9 BD protective criteria and still managed to score 71% points through other criteria and could achieve a good green rating (GREEN SL Gold)

B). GREEN^{SLR} Certification of NES Building

Figure 4.2.5 illustrates the point scored by NES building for all its criteria under the eight aspects regarding BD protection by GREEN^{SLR}.



- NES building has scored 68% points to obtain GREENSLR GOLD
- NES building has scored 51% BD protective points
- Originally GREENSLR contains 76% of BD protective points
- NES has not achieved 25%BD protective points

Figure 4.2.6. BD protective point comparison of NES building - GREEN^{SLR}.

The following criteria were properly achieved by the NES building in the process of taking green certification;
: Site Selection (SS2)
: Reduced Site Disturbance (SS6)
: Storm Water Design, Quality Control (SS8)
: Water Efficiency in Air- Conditioning System (WE2)
: Innovative Wastewater Technologies (WE3)
: Water Use Reduction (WE4)
: Optimize Energy Performance (EA4)
: Renewable Energy (EA5)
: Building Reuse (MR2)
: Construction Waste Management (MR3)
: Resource reuse (MR4)
Therefore, NES has not achieved 25%BD protective points allocated under 11 of BD protective criteria. However, it has managed to achieve a good green rating.

4.3Summery

Table 4.3 Comparison of BD protectiveness of GBRS in terms of case studies

Case study	GBRS	Green Rating and total point obtained by Case Study	Percentage of Pre-requisite criteria (PC)		Percentage of BD protective points	
			Avail-able in GBRS	Scored by case study	Avail-able in GBRS	Scored by case study
IBC	GREEN^{SLR}	Gold (65%)	30%	30%	76%	51%
	LEED	Platinum (76%)	66%	66%	69%	61%
NE WS	GREEN^{SLR}	Gold (68%)	30%	30%	76%	51%
	BLUE GREEN SL	Gold (71%)	0%	0%	65%	46%

5. Conclusions

BD degradation due to buildings is one of such major global scenarios linked to anthropogenic activities. Loss of habitats, habitat fragmentation, natural resource overconsumption, use of many kinds of chemicals like paintings, adhesives, waterproofing materials, pet control chemicals and building emissions, and building affluence are the results of the rapid emergence of buildings. It is a cause of the decline of biodiversity. That is via construction and operation of buildings directly and indirectly contribute to the key environmental pollution types called air pollution, water pollution, and soil pollution linked to global climate change and BD loss. Thus, GBRSs could be identified as one solution to this problem.

The results of this mapping process show that all the GBRS in Sri Lanka contain a considerable weightage on BD protection and those results are in terms of points, LEED contains 69%, BLUE GREEN SL contains 65% and GREEN^{SLR} contains 76%. In terms of PC, LEED contains 66% PC, BLUE GREEN SL contains no PC and GREEN^{SLR} contains 30% PC. Thus, GREEN^{SLR} is the most efficient GBRS as per the BD protective points whilst LEED is strongest as per Prerequisite criteria. The least efficacy has been shown in BLUE GREEN SL under both terms of BD protective points and PC.

According to the present study, it is revealed that GBRS are inefficient in biodiversity protection as it is not a must to obtain a high green rating though there is an impact on biodiversity. Therefore, it is recommended that the efficacy in BD protection of GBRS has to be improved to match local conditions.

Improving the amount of BD protective prerequisites can be identified as one such improvement because the study disclosed that prerequisite criteria play a vital role in deciding the efficiency of Green Rating Systems. Finally, it is recommended to further detail the criteria of GBRS to be able to identify their contribution to biodiversity protection. The lack of availability of high-rated green buildings in different GBRSs for the same building is a major limitation of this study, If can find further case studies in the future regarding this it will help to result in more accuracy.

6. Acknowledgements

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MANUFACTURING SUSTAINABLE PAVING BLOCKS USING POLYMER-MODIFIED BIO-CEMENTATION

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Abstract: Demand for Portland cement is unprecedentedly increasing due to urbanization and related bloom in the construction industry. However, Portland cement is not an eco-friendly material and contributes to several environmental problems. Finding an eco-friendly cementitious material is therefore a current need of the construction industry. In this research, the feasibility of polymer polymer-modified microbial-induced carbonate precipitation (MICP) technique was assessed for sustainably producing paving blocks. In MICP, calcium carbonate ($CaCO_3$) bio-cement is produced artificially by enzymatic urea hydrolysis, in the presence of calcium ions. The efficiency of the process can be accelerated by adding biopolymers, which are herein referred to as polymer-modified MICP. Experiments were conducted at the laboratory scale, and quarry dust specimens were treated using *Sporosarcina pasteurii*, the ureolytic bacteria, with and without the addition of chitosan bio-polymer. Chitosan was introduced to the specimens by mixing and injection. Unconfined compressive strength (UCS) of the casted specimens was determined after 21 and 28 days. The outcomes indicated that the mixing method was more effective compared with the injection. During the injection, a thick $CaCO_3$ layer tended to form at the top of the specimen due to the accumulation of the solutions, which inhibited further penetration of the solutions onto specimens. Compared with the control specimen, the specimen treated with chitosan exhibited higher UCS after 21 days of curing. Chitosan was found to assist in accelerating the formation of $CaCO_3$ and to develop a better bond between particles. Although both the specimens exhibited higher UCS after 28 days of curing, the specimen with chitosan showed lower UCS compared with the control. It was revealed that longer treatment with chitosan led to the formation of higher $CaCO_3$, which blocked the drainage path more quickly than the control specimen. By using polymer-modified MICP, more sustainable paving blocks can be produced against conventional cement blocks.

Keywords: Bio-cementation; Chitosan; Paving block; Microbial induced carbonate precipitation; Compressive strength

1. Introduction

Bio-cementation is an alternative green solution for conventional environmentally unhealthy construction practices mainly for Portland cement. Portland cement is recognized as one of the major construction materials due to its higher strength, durability, and workability. Even though cement is a good engineering material, during cement production large amounts of greenhouse gases especially carbon dioxide (CO_2) are released into the environment (Chang et al., 2016) and it causes global warming and several other environmental issues. Therefore, bio-cement has been recognized as a more environmentally friendly, sustainable green cement material.

Among the bio-cementation processes, urease-based bio-cementation has led to the top in the world. Urease is a nickel-containing enzyme and can be found in some bacteria species and some plant species (Holm et al, 1997). Urease-based bio-cementation can be categorized into two based on the source of the urease enzyme-induced carbonate precipitation (MICP) and enzyme-induced carbonate precipitation (EICP). In MICP, calcium carbonate (CaCO3) is produced artificially through a series of biochemical reactions. Enzyme urease can hydrolyze urea into ammonia and bicarbonate ions and in the presence of the calcium ions, CaCO3 is produced as given in Eq. (1) – (3) (Nawarathna et al., 2018, Fujita et al, 2017, Gowthaman et al., 2019). It has been proven that MICP has been used effectively to solve many civil engineering problems such as ground improvement, liquefaction remediation, enhancing properties of concrete, and so forth in eco-friendly, cost-effective, and sustainable ways (Bachmeier, et al., 2002; Nawarathna et all, 2019, Whiffin et al, 2007; Amarakoon et al, 2017; Gowthaman et al., 2019). The efficiency of the MICP can be further increased sustainably by adding bio-polymers and the process is called polymer-modified MICP. By using polymer-modified MICP, organic-inorganic hybrid green material can be produced with excellent physical properties (Nawarathna et al., 2018, Nawarathna et al., 2019, Wang et al., 2018).

$$\mathrm{CO(NH_2)_2 + 2H_2O \xrightarrow[\text{Urease enzyme}]{} 2NH_4^+ + CO_3^{-2}} \quad (1)$$

$$\mathrm{CaCl_2 \xrightarrow{H_2O} Ca^{2+} + 2Cl^-} \quad (2)$$

$$\mathrm{Ca^{2+} + CO_3^{2-} \xrightarrow{\text{Precipitation}} CaCO_3} \quad (3)$$

However, applications of the bio-cement in the construction field are still limited. Few studies reported the fabrication of bio-bricks using MICP process as a sustainable alternative for clay and masonry bricks. Bernardi et al. (2014) have produced bio-bricks through bio-cementation of the sand using MICP method under full saturation condition. Bu et al. (2018) produced sand bio-bricks using MICP method. They have implemented the immersion method where mold filled with sand immersed in the medium of bio-cementation for seven days and they could be obtained an acceptable level of strength. However, the literature related to the use of urease-mediated bio-cementation technique to produce paving/interlock cannot be found, and, in this research, the first time a bio-compatible paving block was produced by using a polymer polymer-modified MICP process.

Nowadays, paving blocks are extensively used for pedestrian paths, parking lots, etc. and Portland cement is the main material used to construct the paving block. As mentioned above it may cause global warming and several other environmental issues (Chang et al., 2016). Therefore, producing an eco-friendly and sustainable paving block is a current need. Chitosan was used as a natural biopolymer for the experiments. Chitosan is a natural polysaccharide, which is derived from the deacetylation of chitin and it is a cationic biopolymer (Jozwiak et al, 2016; Liu et al., 2015). Chitin is one of the most abundant biopolymers on earth and can be mainly found in the exoskeleton of arthropods, marine diatoms, and certain types of algae (Nistico, 2017; Jozwiak et al, 2016) Chitosan is biocompatible and low toxic biopolymer which is widely used in medicine, agriculture, and wastewater engineering field (Nygaard et al, 2015, Montembault et al, 2004). The use of chitosan-modified urease-based bio-cementation to produce eco-friendly paving blocks will be an interesting initiation for the Sri Lankan construction field.

2. Materials and Methods

2.1 Materials

Chemical reagents and organic materials

- Peptone from meat, Peptone from water, $NCl_2Na_2HPO_4$, Glucose, and Urea where the bacterial culture medium, and urea, $C,,,aCl_2$, and nutrient broth were used to prepare the cementation solution. Chitosan was used as an organic material. Acetic acid and NaOH were used to prepare the chitosan solution.

Quarry dust

- Quarry dust sample was collected and particle size distribution and specific gravity were obtained through laboratory experiments. Particle size between 1.18 mm to 4.75 mm was taken for the experiment

2.2 Methods

2.2.1 Preparation of bacterial cell culture

Ureolytic bacteria, *Sporosarcina pasteurii* (IBRC-M No. 11277) was used for the experiments. Bacteria cells were precultured in Trypticase soy broth medium (5 mL; peptone from meat 17 g/L, peptone water 3 g/L, $NaCl_2$ 5g/L, Na_2HPO_4 2.5 g/L, Glucose 2.5 g/L and urea 20 g/L) by shaking at 30 °C for 24 h. After that, the main culture was prepared by adding 1 ml of the preculture to the 100 mL of the fresh Trypticase soy broth medium. The mixture was kept in the shaking incubator under the same conditions for 48 hours as those used for the pre-culturing.

2.2.2 Preparation of chitosan (biopolymer)

The chitosan with 2% concentration was used for the experiments and 2% chitosan was obtained by dissolving the chitosan powder in 1 % acetic acid solution. After complete dissolution of the chitosan, it was neutralized by 0.1 M NaOH.

2.2.3 Sample preparation

The collected quarry dust sample was sieved through a 1.18 – 4.75 mm sieve and a passing fraction was collected for testing purposes. Quarry dust was placed into the mold (10cm x 10 cm x 5 cm) in three layers and each layer was subjected to 25 hammer blows. Hammer blows were distributed uniformly throughout the surface. Samples were prepared by using both injection and mixing of chitosan.

2.2.4 Sample preparation by mixing method

Quarry dust was mixed well with 2 % (100 mL) chitosan and placed into the mold in three layers as explained above. After that bacteria solution (150 mL) was injected to the top of the sample until saturate the sample and leave it for 30-45 min to allow the bacteria to fix to the quarry dust particles. After 30-45 minutes, cementation solution (150 mL; 0.4 M urea, 0.4 M $CaCl_2$, and 3 g/L nutrient broth) was injected into the specimen, and the solution was drained from the outlet at the bottom, leaving 1 mL of the solution above the surface. The experiment time is 28 days and bacteria solution was injected at the beginning of the experiment and again on the 7th, 14^{th,} and 21st day of the experiment while cementation solution was injected daily. Specimens were removed from the mold after 28 days and kept at room temperature for a few hours before measuring the unconfined compressive strength (UCS) value. A control sample was prepared without mixing the chitosan.

2.2.5 Sample preparation by injection method

The first sample mold was filled with the quarry dust in three layers using the same procedure explained above. Then 2 % (100 mL) chitosan solution was injected from the top of the sample and left it 30 min before injecting the bacteria. After injection of the bacteria solution, leave it for 30-45 min to allow the bacteria to fix to the quarry dust particles. Then cementation solution was injected into the specimen by using the same procedure explained above. Since the curing time was 28 days, bacteria solution was injected into the sample at the beginning of the experiment and again on the 7^{th}, $14^{th,}$ and 21^{st} day of the experiment while cementation solution was injected daily. After 28 days the sample was removed from the mold and the UCS value was measured. A control sample was prepared without injecting chitosan. Figure 1 shows the experimental setup.

Figure 1: Experimental Setup.

Since, injection of the chitosan didn't give positive results, mixing of chitosan was selected for further analysis. Paving blocks were prepared by changing the treatment time and with/without chitosan addition as given in Table 1. At the end of the curing time, samples were removed from the mold and UCS values were determined.

Table 1: Experimental conditions

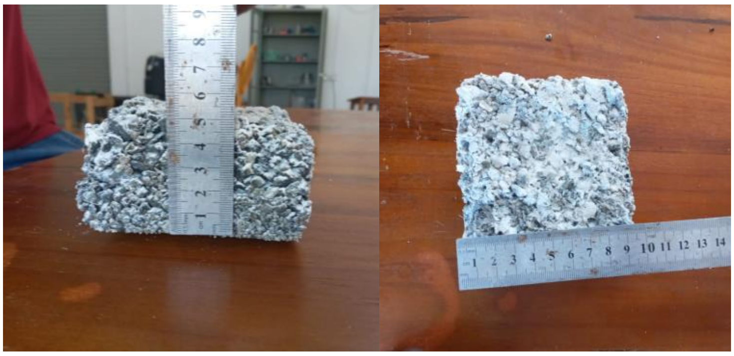
Bacteria injection	Addition of chitosan	Experiment duration
3 times (1^{st},7^{th} and 14^{th} day)	Yes, by mixing	21
3 times (1^{st},7^{th} and 14^{th} day)	No	21
4 times (1^{st},7^{th} and 14^{th}, 21^{st} day)	Yes, by mixing	28
4 times (1^{st},7^{th} and 14^{th}, 21^{st} day)	No	28

3. Results and Discussion

3.1 Experiment with chitosan injection and mixing

Initially, samples were prepared separately by mixing and injecting chitosan. After 28 days of the curing period, samples were removed from the mold. Compared with an injection of the chitosan, mixing of the chitosan gave positive results. The sample with the injection of the chitosan didn't cement properly and a thick $CaCO_3$ layer was deposited on the top of the paving block as shown in Figure 2 (a). Chitosan solution was injected from the top of the sample, and it penetrated the sample through pore spaces using gravity. Therefore, more chitosan hydrogel has been precipitated at the top of the sample. Similarly, bacteria and cementation solution were also injected from the top of the sample. Therefore, a large amount of $CaCO_3$ has been precipitated on top of the sample and it prevents the penetration of the solutions after some days and leads to a decrease in $CaCO_3$ formation inside the sample. To have a better cementation, pore spaces between the quarry dust particles should be filled effectively by $CaCO_3$ and it should form a better bridge between the particles (Harkes et al., 2010). By mixing the chitosan solution with quarry dust, a good, cemented sample could be obtained as shown in Figure 2 (b). Chitosan solution was distributed uniformly during mixing and $CaCO_3$ formed effectively throughout the sample rather than depositing at the top. Since the mixing of chitosan is more effective for bio-cementation, further experiments were carried out using the mixing method.

(a)



(b)

Figure 2: Sample treated (a) with injecting chitosan (b) without chitosan.

3.2 Experiment with and without chitosan mixing under different experimental conditions.

Different samples were prepared by changing the treatment time (21 days and 28 days) with and without mixing chitosan as given in Table 1. For 21 days of samples, bacteria were injected 3 times (1^{st},$7^{th,}$ and 14^{th} day) and cementation solution was injected daily. After 21 days, samples were removed from the mold and as shown in Figures 3 (a) and (b) samples were properly cemented. UCS values of the samples were measured after 21 days and the sample without mixing chitosan gave a lower UCS (0.67 MPa) value compared with the sample with chitosan (0.93 MPa). It seems chitosan has assisted in filling the pores effectively and making better cementation. Chitosan is a cationic biopolymer and charged positively in an acidic medium (Jozwiak et al, 2016; Liu et al., 2015). However, in the alkaline medium, it can create its hydrogel due to deprotonation of the amino groups (Nygaard et al, 2015). Here, due to the formation of the ammonia, the reaction mixture has a weak alkaline condition, and it is favorable for the chitosan solution to make its hydrogel by the hydrogen bonds and hydrophobic interaction between molecules (Nawarathna et al., 2019, Nygaard et al, 2015). This hydrogel assisted in forming a better bond between the soil particles. Also, chitosan acts as a template for $CaCO_3$ to nucleate and grow. On the other hand, chitosan can upgrade the $CaCO_3$ formation efficiency (Nawarathna et al, 2019). Due to these reasons, a specimen with chitosan has higher cementation and strength compared to the sample without chitosan due to the proper filling of the pore spaces between the quarry dust particles. Not only the filling of the pore spaces but also making better bonds at the contact point of the soil/quarry dust particles is also important to have better solidification (Cheng et al., 2016). Formed chitosan hydrogel support to connect the particles. In addition to the strength gained, by adding chitosan, the brittleness of the specimen can be reduced. Brittleness is one of the main drawbacks of the MICP-treated samples (Rahman et al., 2020).

(a)

(b)

Figure 3: 21 days treated samples (a) with chitosan (mixing) (b) without chitosan.

Similar experiments were conducted for 28 days treating samples where bacteria were injected 4 times (1^{st},7^{th},$14^{th,}$ and 21^{st} day) and cementation solution was injected daily. After 28 days, samples were removed from the mold and as shown in Figure 4 (a) and (b) samples were properly cemented. UCS values of the samples were measured after 28 days and in contrast to the 21-day samples, the sample without mixing chitosan gave a higher UCS (1.15 MPa) value compared with the sample with chitosan (0.97 MPa). As mentioned earlier, chitosan increases the efficiency of the $CaCO_3$ formation. After 3 weeks of treatment, the sample with chitosan reduced the penetration of the bacteria as well as the cementation solution due to the blocking of the pore spaces near the top of the sample and inhibited the efficiency of $CaCO_3$ formation. This would be the most possible reason for getting a lower USC value for the sample with chitosan compared with the control sample during a long treatment time. Better results would be obtained by reducing the chitosan concentration. However, compared with the 21-day samples, a higher UCS value could be obtained for the samples within 28 days of treatment. Increasing the treatment time led to forming more $CaCO_3$ and filling of pore spaces effectively. Therefore, a higher UCS value could be obtained by increasing treatment time.

(a)

(b)

Figure 4: 28 days treated samples (a) with chitosan (mixing) (b) without chitosan.

4. Conclusion

In this study, the effect of the polymer-modified urease-mediated bio-cementation method to fabricate a sustainable paving block was investigated. The following are the main conclusions from the current study.

i. During lower treatment time, samples with chitosan give higher UCS due to better filling of the pore spaces by chitosan hydrogel and higher efficiency of the $CaCO_3$ formation on the chitosan template.
ii. However, for longer treatment time, a sample with chitosan gives lower UCS compared with the control sample. Longer treatment with chitosan led to the formation of higher $CaCO_3$, which blocked the drainage path more quickly than the control specimen.
iii. In both cases (with and without chitosan), the UCS value increases with the increase of treatment time.
iv. Mixing chitosan solution with quarry dust is more effective than injecting chitosan solution. A very thick $CaCO_3$ layer has formed for the sample with chitosan injection and exhibits lower cementation due to the lack of penetration of bacteria and cementation solutions throughout the sample.
v. Finally, it can be concluded that polymer-modified MICP is a more sustainable and eco-friendly approach to producing more sustainable paving blocks against conventional cement blocks. However, future experiments need to be conducted to increase the strength.

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A STUDY ON ENHANCING AIR QUALITY AND THERMAL COMFORT USING NATURAL VENTILATION IN A LARGE AUDITORIUM

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Abstract: Natural ventilation, the process of using outdoor air to cool and ventilate indoor spaces, is an energy-efficient and sustainable approach to building design. The E.O.E. Pereira theatre at the Faculty of Engineering, University of Peradeniya, with a capacity of 660 seats, has been identified to be uncomfortably warm during its use. This scientific writing aims to explore the existing problems and strategies to create good air quality within the theatre. An extensive Computational Fluid Dynamics (CFD) simulation was carried out to identify the temperature variations, supply of fresh air and airflow patterns in the theatre on the current operating configuration and several improved configurations. The study explores key considerations such as louvre configuration, age of air, thermal comfort, and how external factors such as fans or blowers could be used to further improve the air quality inside the theatre. The findings and conclusions from the CFD simulation analysis provided useful insights about the most suitable configurations that can be adopted to improve the comfort of the audience in the theatre. Considering financial factors, two configurations were chosen for further analysis. From the first configuration, which is economical, the simulation revealed that the audience would receive a 100% improvement when considering the age of air compared to the current operating configuration, where the age of air is 280 seconds. The thermal comfort is also improved by 3^{o}C in the neighbourhood of the audience. Alternatively, when comparing the costly configuration, the results revealed a 3.5^{o}C improvement in thermal comfort and an improvement of the age of air to 170 seconds near the audience, but conditions on the stage improved drastically. The findings of this study can be used in implementing design measures that promote indoor air quality, thermal comfort, and energy efficiency.

Keywords: Natural Ventilation; Sustainable Buildings; Computational Fluid Dynamics; Age of Air; Thermal Comfort

1. Introduction

Proper utilization of natural lighting and ventilation offers significant benefits, including substantial energy savings of 10% to 30% compared to air-conditioning (Walker, n.d.). Natural ventilation systems rely on natural forces like wind and buoyancy to deliver fresh air into buildings, using pressure differences caused by wind or temperature variances (Walker, n.d.). Crossflow of wind induces positive and negative pressures, leading to fresh air entering on the windward side and exhausting on the leeward side, with factors like wind angle and opening size affecting airflow (Walker, n.d.). Architectural features, like casement windows, and tiered seating can facilitate airflow. Buoyancy, driven by temperature differences, causes warm air to rise and exit through upper openings, while lower openings allow fresh air in, mitigating negative pressure (Walker, n.d.).

Indoor air quality in such buildings can be assessed in terms of air changes per hour (ACPH), with a recommended range of 4 to 15 for auditoriums (ASHRAE, 2004; Turner et al., 2008, 2010). Air quality is mainly influenced by particulates, microbial organisms, and gaseous pollutants (Indoor Air Quality - Continental Fan, n.d.). Research by Adjiski et al. (2018) suggests a method using a User Defined function (UDF) in Computational Fluid Dynamics (CFD) software to measure air change effectiveness, especially in underground mines. The E.O.E. Pereira Theatre at the University of Peradeniya is frequently packed with over 600 occupants, yet its original natural ventilation system, consisting of manually operated louvres, has proven ineffective in providing adequate ventilation. This issue is exacerbated by the inaccessibility of louvres closer to the ceiling at a height of 6.3 meters from the floor, resulting in their closure. Additionally, the dark paint on the glass panels further restricts natural light, posing a challenge when balancing ventilation needs with the desire to minimize light entry.

Considering these concerns, this paper explores the different configurations of louvre arrangements aimed at enhancing thermal comfort and air quality within the E.O.E. Pereira Theatre. The effectiveness of these configurations was validated by conducting an extensive Computational Fluid Dynamics (CFD) simulation, the results of which are presented in this paper. This study seeks to address the pressing need for improved ventilation in the theatre and its potential impact on overall air quality, laying the foundation for a more comfortable and favourable environment for its occupants.

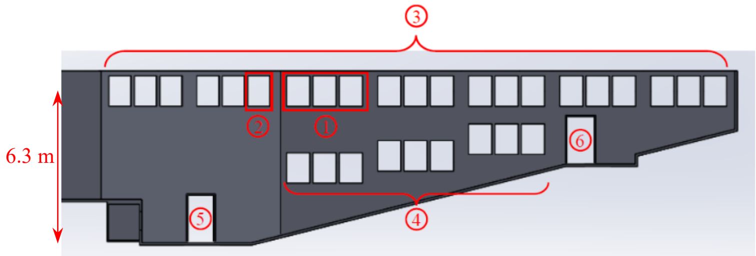


Figure 01: Louvre arrangement on one side of the theatre.

A detailed view of a side wall of the theatre is shown in Figure 01, highlighting the specific locations of the louvres under consideration. The numbers 1 to 6 show a set of louvres, a louvre, upper louvres, lower louvres, front door, and the rear door, respectively. Within the theatre, a total of 66 individual louvres are installed, grouped into sets of 3, as depicted in Figure 01. Notably, approximately 50% of these louvres, comprising 36 units or 12 sets, are rendered inaccessible due to their elevated position. Each side of the theatre is equipped with 2 doors for entry and exit. In addition, there are grills at the rear of the theatre beside the control room. A CFD simulation is used to determine the characteristics of the airflow in the theatre such as temperature variations, age of air, air flow velocity, flow path, and direction. The simulation aims to replicate the actual conditions to a great extent by using realistic parameters and heat load. The conclusions from the CFD simulation will be greatly supportive in making decisions about improving the comfort of the audience in the theatre.

2. Methodology

2.1 Theatre Modelling

The entire theatre and its immediate surroundings were modelled using SolidWorks. An inclined plane was used for the seating area of the theatre instead of modelling the actual seats. An adjusted heat load could be applied to the inclined plane, thus minimizing the complications related to modelling all the seats in the theatre. Figure 02 shows the outside view of the modelled theatre and Figure 03 (a) shows half of the interior of the modelled theatre. Figure 03 (b) shows the theatre when the upper louvres are closed. The symmetricity of the theatre was taken into consideration during the simulation; hence, all simulations were conducted only for one-half of the theatre.

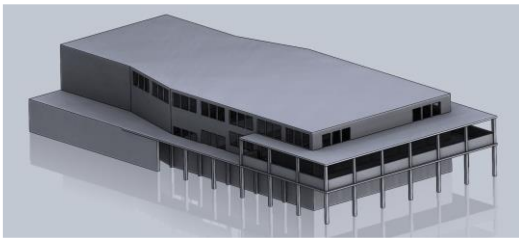
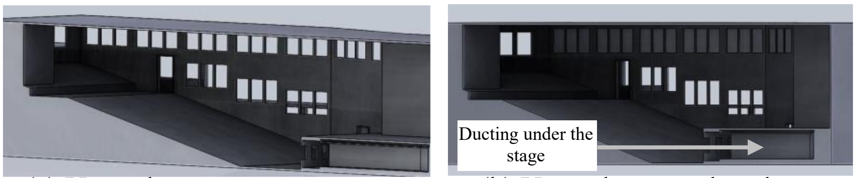


Figure 02: Outside view of the modelled theatre.



(a) Upper louvres open (b) Upper louvres closed

Figure 03: Inside view of the theatre.

This model was used in various configurations to obtain airflow patterns and the air quality of the theatre. The air domain was extracted from this model using a significant amount of air in the surroundings as well. The air domain extraction was done using SolidWorks and the extracted air domain was used in Ansys for the CFD Simulation to obtain various parameters. The theatre already consists of an exhaust system which can pump out air through a ducting available under the stage of the auditorium as shown in Figure 03 (b). The mass flow rate of this system is determined to be 9.866 kg/s. For this study two configurations were selected to be analysed; (i) the configuration with existing facilities and (ii) another configuration with an additional exhaust system installed at the rear of the theatre.

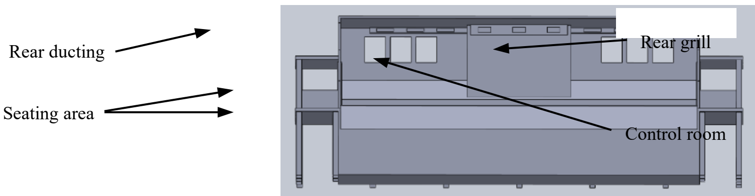


Figure 04: Cross-sectional view of the rear of the theatre.

The proposed rear exhaust duct system is shown in Figure 04 where it is designed to have a collective flowrate of 2 m3/s. This amounts to an air removal of 2.37 kg/s. The ducting was designed to fulfil the required mass flow rate.

3.2 Heat Load Calculation

The heat load inside the theatre under full capacity is a crucial factor in this CFD simulation. Heat load was calculated assuming 600 occupants inside the theatre. The heat flux from the human body of an average person was taken to be 60 W/m2 when the person is seated at rest and the body surface of an average man was 1.8 m2 (ASHRAE 55, 2010; Turner et al.). The modelling of the theatre was done considering a heat flux of 235.64 W/m2 as emitted from 600 occupants proportionate to the theatre seating area. These approximations were used for the simulation since the actual temperature inside the theatre at full capacity could not be recorded due to the restrictions imposed during the research period which coincided with the Covid-19 pandemic.

The existing front exhaust fan was considered for simulations. Since the airflow path under the stage is symmetric, no harm was done by taking only one-half of the mass flow rate for the simulation, 4.933 kg/s as applied by the front exhaust fan. The average outside temperature in the surroundings of the theatre was considered as 26.85 °C (300 K). This is a moderately warm temperature at Peradeniya and was considered suitable for the simulations as the importance of airflow comes into play only when the ambient temperature is relatively high.

3.3 Modelling Parameters and Validation

The modelling parameters were selected considering atmospheric conditions and airflow patterns in the theatre premises. The E. O. E. Pereira Theatre is situated in the middle of the faculty premises covered by several two-story buildings. Therefore, the airflow around the theatre was neglected to achieve the worst-case scenario of the simulation. The effect of solar radiation was not considered in the simulations. The pressure-based approach is used for low-speed less compressible flows, while the density-based approach is used for high-pressure compressible flows. Since the air volume inside the theatre has low speed and the compressibility of air is negligible due to natural ventilation, a pressure-based approach was used for simulations.

The Boussinesq approximation is used to define fluid density. In the field of buoyancy-driven flow, the Boussinesq approximation is applied. It is assumed that density fluctuations have little effect on the flow field other than to cause buoyancy forces. The buoyancy force is one of the major driving forces of natural ventilation systems. Since the theatre was originally designed with a natural ventilation system, the buoyancy effect is an essential factor that needs attention. The energy equation is used for problems involving heat transfer. It considers the energy transfer due to conduction, viscous dissipation, and any other stated volumetric heat source. Since one of the objectives of this study is to investigate the temperature variations inside the theatre, the energy equation was turned on.

The k-epsilon model was used in this simulation since it is specifically designed for recirculating flows. It is usually used for flows with relatively small pressure gradients (AnsysInc., n.d.). However, the k-epsilon model is also normally used to simulate mean flow characteristics for turbulent flow conditions. Even though the airflow to be expected inside the theatre is laminar, the k-epsilon model is used as a precaution in case there are recirculating flows especially because of the low-pressure gradients. SIMPLE (Semi-Implicit Method for Pressure Equations - Consistent) is chosen as the pressure-to-velocity coupling scheme. When compared to the SIMPLE model, this approach can improve the amount of under-relaxation that may be applied and hence provide convergent solutions faster. To achieve a compromise between simulation accuracy and cost/speed, the spatial discretization gradient is also configured as Green-Gauss cell-based gradients, which are suitable for moderate and low skewness meshes, respectively. Since the meshing of the air volume inside the theatre is not complicated and has low skewness, the selected gradient will be suitable for the purpose (AnsysInc., n.d.).

Because the simulation is not being run under constant environmental conditions, hybrid initialization is the best option. Standard initialization simply fills the properties with constant values for all the elements, whereas hybrid initialization solves a simplified equation system with up to ten iterations. As a result, hybrid initialization usually yields a more accurate estimate of the flow variables (AnsysInc., n.d.).

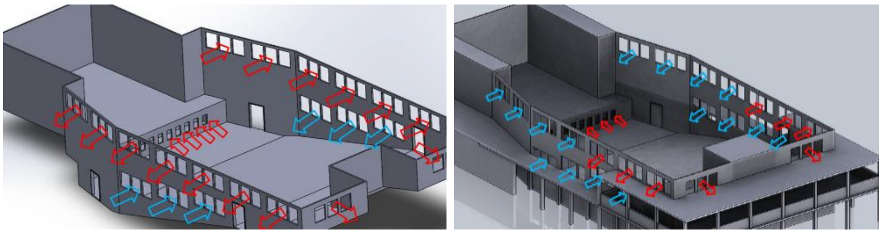
3.4 User-Defined Function for Air Quality Calculation

The age of air can be described as the time that a particular particle of air has spent inside the theatre. The age of air of a particular particle is considered zero at the point on the boundary where it enters the area being simulated. The age of air is expressed in seconds. Thus, a lower age of air means the air is fresher. A supply of fresh air would increase the comfort level of the audience. A higher value for the age of air indicates that air which has been stagnating inside the theatre is present in that location. Using the Airflow patterns generated the software can calculate, using a user-defined function, how long it will take for a fresh air particle to reach a specific location and hence display the parameter called Age of Air measured in seconds.

4. Results

4.1 Air Flow Patterns

It was expected that the airflow pattern in the E.O.E. Pereira Theatre would be as shown in Figure 05 (a); i.e., it was thought that fresh air would enter the theatre from the lower louvres and warm air would escape through all the upper louvres and the front exhaust fan vents. This was due to the application of the buoyancy effect.



(a) Expected pattern (b) Actual pattern

Figure 05: Airflow patterns inside the theatre.

Subsequently, when the CFD simulations were carried out, a slightly different airflow pattern was observed. Figure 06 shows the velocity vector diagram of the airflow in the theatre in a horizontal plane across the upper louvres. Accordingly, it is observed that the front upper louvres allow fresh air to enter the theatre whilst the rear upper louvres allow warm air to escape the theatre. This flow pattern is shown in Figure 05 (b).

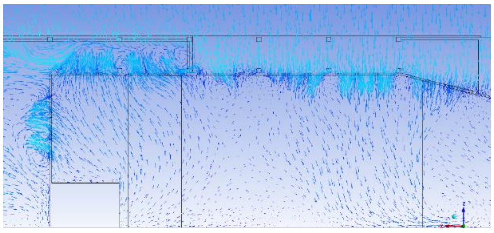


Figure 06: Air velocity map in a horizontal plane across the upper louvres.

4.2 Temperature Variations for Thermal Comfort

Considering the first configuration with existing facilities, the first simulation investigated the effect of opening the upper louvres of the theatre. This results in a significant improvement in temperature conditions inside the theatre. Figure 07 shows the temperature variations in a vertical longitudinal plane across the middle of the theatre (consisting of the control room at the rear) when the upper louvres are closed and open respectively. Heat dissipation from the seating area has been improved with the opening of upper louvres. That would increase the comfort of the audience.

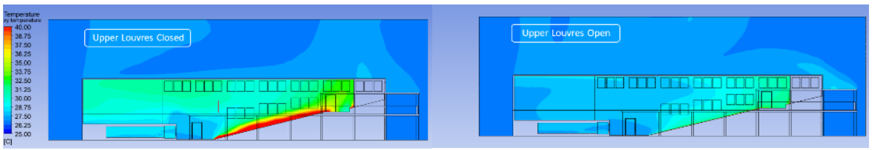


Figure 07: Temperature variation comparison in mid-plane, when upper louvres are closed and opened.

The vertical plane shown in Figure 08 is between the side wall of the theatre and the midplane. It can be observed that hot air rises towards the rear of the theatre due to the buoyancy effect. Since this hot air only escapes through the existing rear grill, when the upper louvres are closed, the temperature rise at the back of the theatre is significantly high. A temperature difference of approximately 5 °C was noted between the front and the rear of the theatre before the upper louvres were opened.

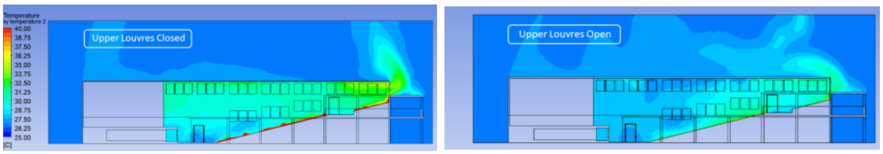


Figure 08: Temperature variation comparison in a plane across the rear grill with upper louvres closed and opened.

The plane taken in Figure 09 is an inclined plane parallel to the audience at a 1 m height. We could observe the reduction of temperature across the theatre from the front to the back as mentioned earlier. The overall temperature in the seating area has dropped by 3°C on average. This confirms that thermal comfort can be improved by allowing the hot air to escape that accumulates at the back of the theatre due to the buoyancy effect.

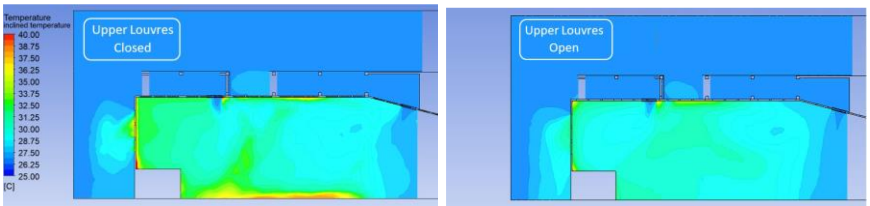


Figure 09: Temperature variation comparison in a plane across occupant seating area when upper louvres are closed and opened.

Since the above simulations, Figures 07 – 09, with existing facilities in the theatre show a collection of hot air at the rear of the theatre, another configuration-using a rear exhaust duct was investigated. Figures 10 –12 show variations in temperature along several planes in the theatre with and without the rear exhaust duct system. It can be observed from Figure 10 that the accumulation of warm air in the vicinity of the audience seated right in front of the control room can be improved by applying a rear exhaust system. In addition, Figure 11 also shows that there is a slight improvement in thermal comfort towards the rear of the theatre. Quantitatively, it can be noted that a maximum reduction of approximately 3.5°C is possible compared to the current operating condition.

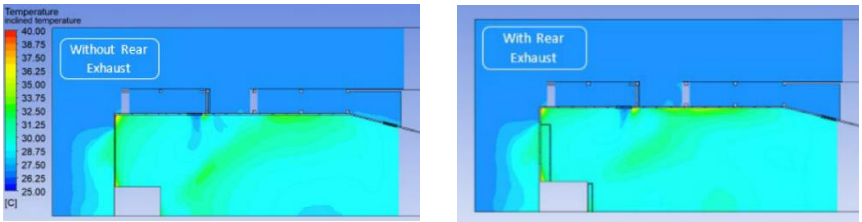


Figure 10: Temperature variation in an inclined plane across occupants' seating area without and with rear exhaust duct.

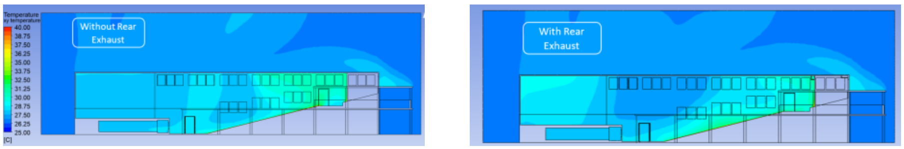


Figure 11: Temperature variation in a vertical plane across the mid-plane without and with the rear exhaust duct.

When looking at the temperature distribution in Figure 12, which depicts a plane in between the mid-plane and the wall of the theatre, it can be seen that there is no significant change in the temperature distribution towards the front of the theatre. However, the thermal comfort of the audience seated on either side of the control room at the rear of the theatre is improved marginally.

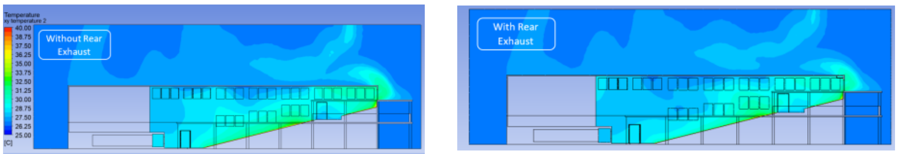


Figure 12: Temperature variation in a vertical plane across the rear grill without and with the rear exhaust duct.

4.3 Air Quality Index

The Air quality measurement was obtained using the mean age of air calculated from a user-defined function applied in Ansys. The 3D volume rendering of the entire theatre with upper louvres closed and upper louvres open are shown in Figure 13 and the air quality of the inclined plane consisting of the occupants for the same 2 cases is shown in Figure 14.

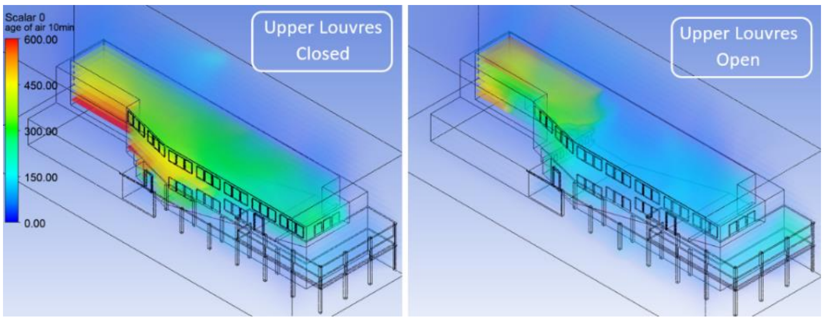


Figure 13: 3D view of the variation of age of air in the theatre when the upper louvres are closed and open.

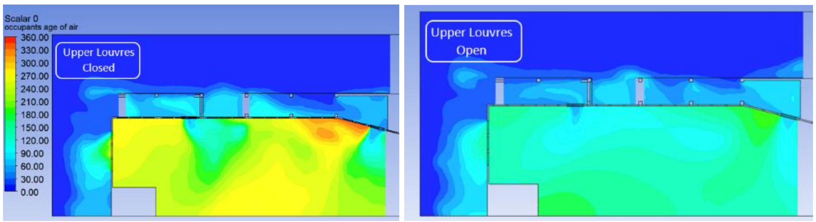


Figure 14: Variation of age of air in an inclined plane through the seating area when the upper louvres are closed and open.

According to these two Figures, it is evident that there is a significant reduction in the age of air within the theatre when the upper louvres are open. Therefore, opening the upper louvres will significantly increase the comfort of the audience. Considering with and without the rear exhaust system, it can be seen from Figure 15, that there is suction of fresh air through the rear door which directly flows towards the rear duct without allowing it to flow towards the centre of the theatre. This suction effect of air from the rear door can be seen in Figure 12 as well. Due to this reason, the age of air in the mid-centre area of the theatre will be older when operating with the rear exhaust system as compared to without the exhaust system. It could be seen that even though there is a significant improvement in the mean age of air, from 280 s to 140 s, when the upper louvres were opened, the age of air increases to 170 s when operating with the rear exhaust system.

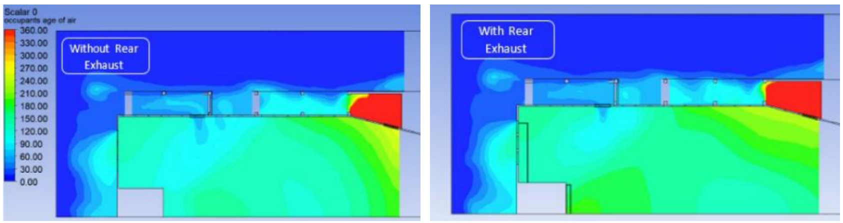


Figure 15: Variation of age of air in an inclined plane through the seating area without and with rear exhaust duct.

5. Discussion and Conclusion

The Computational Fluid Dynamics (CFD) simulations have provided numerous findings that support decision-making to enhance the comfort of occupants in the theatre more sustainably by utilizing natural ventilation as much as possible. A significant conclusion is that being able to open the upper louvres of the theatre greatly improves the comfort of the audience. The comparison between the configuration of keeping the upper louvres closed vs opening them has shown increments in both thermal comfort and air quality. A temperature difference of approximately 5°C was noted between the front and the rear of the theatre in the existing louvre structure (with upper louvres closed) due to the hot air being trapped at the back of the theatre. A noticeable reduction of the temperature difference between the front and rear of the theatre has occurred by allowing fresh air to enter from the upper set of louvres at the front of the theatre and then for the hot air to escape through not only the rear grill but also through the rear sets of upper louvres. An average temperature reduction of at least 3°C is noted, thus increasing the comfort level of the occupants in the rear of the theatre. Furthermore, operating the front exhaust fan increases the supply of fresh air to the seating area. The air quality near the audience has improved from 280 s to 140 s.

The comparison between the configuration of upper louvres being opened with the second configuration has led to the conclusion that the implementation of a rear exhaust system will marginally increase thermal comfort by about 0.5°C. In addition, in the air quality assessment, the mean age of air has increased from 140 s to 170 s thus worsening air quality.

Therefore, it was concluded that implementing the rear exhaust would not be cost-beneficial. The economic arrangement would be the optimum solution based on a cost-benefit analysis.
With the findings of this study, where the upper louvres had a significant impact on air quality and thermal comfort, a central control system to operate the entire set of louvres in the theatre was subsequently developed.

Acknowledgements
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EFFECT OF ENERGY DEMAND AND THERMAL COMFORT OF LOW-INCOME HOUSES; CASE OF MONARAGALA DISTRICT

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Abstract: Within the next 30 years it is estimated that half of the world's population will reside in developing countries of Asia and Africa. Thus tropical urbanization increases the demand for places for people to live and the increasing level of energy demand. The domestic sector dominates the electricity consumers of the country and is evident for the highest end-user energy demand of 34% on the national grid. Although the national electrification level is 99.7% few districts have not achieved the status of 100% accessibility to electricity. This study explores the energy demand levels and thermal comfort aspects of the low-income houses of the poverty-stricken district of Monaragala. This district contributes 3.2% to the total poverty levels of Sri Lanka. Findings indicate 25% of the sample falls into this category of being below the poverty line, which is higher than the 23% national estimate. Results indicated that the mean electricity consumption is 51 kWh per household per month whilst only 25% had access to clean cooking fuels. Furthermore, findings indicated that the internal spaces are overheated with an operative temperature of 32.2°C and this temperature does not comply with ASHRAE 55 standards. The required comfort temperature, according to the comfort temperature equation is 28.92°C. However, the investigated operative temperature is 3.3°C more. Thus, these findings highlight the importance of implementing a housing approach for low-income houses, prioritizing climate change and the well-being of the occupants in tropical climate contexts. This accomplishes the interaction of several United Nations Sustainable Development Goals (SDGs), with six principally significant SDGs such as poverty (1), health (3), infrastructure (9), inequalities (10), cities (11), and climate (13).

Keywords: Thermal comfort; Energy demand; Low-income houses; Tropical urbanization

1. Introduction

Sustainable Development Goals (SDG) or Global Goals are the concepts that carry out a more prosperous, sustainable, peaceful, and fairer world in which no one is left behind (Elliott, 2012). These SDGs are applied similarly to developing and developed countries. The SDGs were developed based on three key dimensions known as ecological, social, and relational inclusiveness with five principles each (Gupta and Vegelin, 2016). There are 169 targets and 232 indicators including 17 Sustainable Development Goals introduced by the United Nations (Gossling-Goidsmiths, 2018).

Asia is one of the fastest-growing regions in the world, and for the next 30 years more than half of the global population will concentrate on developing Asian cities (UN,2014). Urbanization in South Asia increases the demand for more places to live and the ever-growing energy demand. The greatest global challenge and the greatest requirement is eradicating poverty in all its forms and dimensions for sustainable development (Elliott, 2012). Poverty is a multidimensional problem (Alkire and Santos, 2013). However, has been measured with only one dimension which is income (Alkire and Santos, 2013). Sri Lanka is a lower-middle-income country of 21.4 million people with a growing economy. The Official Poverty Line (OPL) for Sri Lanka was Rs. 4,166.00 per month per person in 2016 (Department of Census and Statistics, 2016). According to the household survey conducted by the Department of Census and Statistics, approximately there 3.1% (169,392) of the total households were poor in 2016.

The negative consequences of climate change especially heat stress cause distress among vulnerable human groups of low-income households living under the poverty-stricken bracket. This aspect further delays their recovery period as the occupants do not experience satisfactory levels of thermal comfort. Thermal comfort has been defined as "the condition of mind that expresses satisfaction with the thermal environment" (ISO 7730, 1994). It is the satisfactory perception of the thermal environment which assessed subjectively.

With sustainable goals to be met by 2030, SDG 7 on energy sets the goal of ensuring that everyone has access to affordable, dependable, sustainable, and modern energy. Sri Lanka committed to reducing GHG emissions from energy by 4% unconditionally and 16% conditionally (compared to the baseline year of 2010) by 2030 as part of an Intended Nationally Determined Contribution (INDC). To become carbon neutral by 2050, increasing the capacity of renewable energy is thus a bold goal in the integrated national energy policy.

The majority of the nation's power users are in the domestic sector, which is seen from the national grid's highest end-user energy demand of 34%. Even though 99.7% of the country is electrified, there are still a few districts that do not have complete electrical accessibility. In the districts stricken with poverty, a majority of the households do not have access to electricity. One such district is Monaragala as this district contributes 3.2% to the total poverty levels of Sri Lanka. It's crucial to investigate the impact of housing types on the energy consumption patterns of low-income settlements in the rural sector because energy equity and poverty are the SDGs' guiding objectives. Therefore, the objectives of this study are to explore the energy demand levels and thermal comfort aspects of the low-income houses of the poverty-stricken district of Monaragala.

2. Materials and Methods

2.1 Location and Sample Population of the Study

The study was conducted within the fifteen Grama Nilahari divisions situated in the Monaragala district. These Grama Niladaro divisions include Udagama, Kumarapura, Kumaragama, Dikyaya, Maligavila, Weheragala, Maduruketiya, Gonaganara, Konketiya, Rahathangama, Kukurampola, Uda arawa, Mahagodayaya and Horabokka. Data was collected from 350 houses and analyzed related to the Monaragala district. The Monaragala district experiences a hot humid climate with little or no seasonal variation of temperature annually. The average temperature varies from 28 to 33 °C.

The poverty line is determined by the average monthly expenditure for each person to achieve their basic needs (SPARC, 2011). According to the Department of Census and Statistics Sri Lanka, the official poverty line for each household at the national level for December 2019 was 108.55 USD (Rs. 19 756). As a result, a family is considered to be poor if its average monthly income is below the national poverty level. Results indicated that 25% of the families in the sample under study fall into this category, which is higher than the 23% national estimate. This suggests that a sizable portion of households experience extreme poverty.

2.2 Assessing Energy Poverty

In terms of basic electricity requirements, two approaches are used. These include a top-down approach and a bottom-up approach, where the average amount of electricity utilized by households living below the poverty line is taken into account. PUCSL reports that it is 12 kWh per person each month. The "most essential electrical appliances" are the focus of the top-down strategy, which also includes estimating how much electricity is needed to run each device for a practical amount of time. It is predicted to be 15 kWh per person per home each month, based on the usage of a TV for 4 hours, an electric iron for 30 minutes, a single-door mini-fridge for 24 hours, a fan for 4 hours, mobile charging, and a kettle. According to this study, an average household needs about 60 units to maintain a decent standard of living and satisfy occupant comfort with energy-efficient electronic appliances. The Sri Lankan government has heavily subsidized up to 60 units in the tariff system through the Ceylon Electricity Board (CEB) domestic tariff category. Another standard for determining if hidden energy poverty exists is whether the percentage of power spending is less than half of the national median share (Rademaekers et al, 2014), this aspect is also investigated.

2.3 Assessing Thermal Comfort Levels of Interiors

An onsite field investigation was carried out to obtain the measurement of indoor environmental parameters. Table 01 illustrates the equipment used to obtain these measurements. All the measurements are taken in the month of April 2022.

Table 1: Equipment Used to Obtained the Measurements *Source: By Author*

	Parameter measured	**Equipment used**	**Place of measurement**
1	Indoor temperature	HOBO Temp/ Temperature data logger	In two locations inside thehome (bedrooms)
2	Relative Humidity	HOBO humidity/ Humiditydata logger	In one place immediately inside the building.
3	Wind Velocity	Anemometer	In the same place where the HOBOs were placed indoors.

The indoor thermal microclimatic parameters were obtained within 1m from an individual and of a height of 0.6m from the floor. The period for the measurements was every 10 seconds (ISO, 2001). The operative temperature and mean radiant temperature were calculated using standardized formulas.

3. Results and Discussion

3.1 Energy poverty evaluation

Electricity was always seen as a luxury good in Sri Lanka, but now that rural areas have been electrified, every household can afford it. Although it has become a basic need over time, there is no clear definition of what the Basic Need of Electricity (BNE) is because it differs widely from person to person depending on viewpoints and financial situation. BNE is defined in this case study as the collection of vices utilized by more than 50% of the population. The usage of electronic devices includes mobile phones (87%), televisions (75%), fans (53%), and electric kettles (40%). Additionally, a sizable majority of families use an electric motor (45%) and iron (47%). The typical number of lights utilized is seven, with mean values of two.

Over 50% of the households (59%) consumed fewer than 60 units per month. Some consumers take various actions to limit their consumption below 60 units as rates increase. Near the end of the month, the refrigerator and the motor are typically turned off in most homes. While this may appear to be an energy-saving measure and show a positive trend in energy conservation, in reality, it is a reflection of a state of hidden energy poverty that degrades quality of life. Addition- ally, if a consumer can't stick to their budget or limit, they are encouraged to participate in illegal conduct by convincing the meter reader to add two or three units to their subsequent month's bill. These actions need to be mitigated.

The maximum, minimum, and average monthly power usage for the population in these low-income households were 130, 0, and 51 units, respectively. In comparison to the national mean, the average is much lower. The average cost of electricity is also considerably less than the 442.81 LKR that the national median proportion of consumers spends on power. The findings demonstrate the existence of hidden energy poverty.

The mean electricity consumption is 51 kWh per household month-1. Results indicate that the major fuel type used for cooking in the Monaragala district. Results inform that firewood was used in 93 percent of households. Only 7% of the population has access to clean fuel. This informs that a majority of the population has no access to clean fuel for cooking and no proper electrical cooking equipment.

3.2 Thermal Comfort Evaluation

The air temperatures can fluctuate with the mean radiant temperatures in areas with large interior masses. To evaluate the thermal comfort of the people in the interior spaces, this element might be extremely helpful. As a result, the air temperature (Ta), mean radiant temperature (MRT), and wind speed are used to calculate the operational temperature (Top), which is a crucial indicator of human comfort.

The formula which is used to calculate the operative temperature is as follows.

$$Top = \frac{Ta\sqrt{10v} + MRT}{1 + \sqrt{10v}}$$

Investigations were done on how the interior operating temperatures and wind speeds varied throughout all of the low-income households' indoor spaces. The average operative temperature is 32.2°C, with temperatures ranging from 29°C to 33°C with most occurring (mode) between 30°C and 33°C m/s. These are aided by low velocities, as a majority of the frequency of the range of the wind velocity is between 0.06 to 0.29m/s. The mean wind velocity is 0.23m/s. As the wind velocities are very low, the operative temperature tends to increase, and this proves that the level of ventilation received into the interiors is not adequate and the design measures need to be undertaken to improve this aspect.

The above section describes the existing interior temperatures of the low-income households in Monaragala. These need to be compared with the standard comfort range of temperatures. The ASHARE 55-2013 standard for comfortable thermal conditions, is that the temperature should be within the range of 19- 28°C at 80% humidity levels. There are established thermal comfort ranges in some tropical countries such as in Thailand (Busch et al, 1992) the comfort temperature range is between 25.6°C-31.5°C. The operative temperature obtained is above the thermal comfort range, proving that the interiors of these low-income households are overheated.

Studies have proved that there is a correlation between this comfort temperature and the outdoor temperature (Humphreys, 1992 and Ni- col, 2004). According to Humphreys (1992), there is a relationship between the comfort temperature and mean outdoor temperature for naturally ventilated buildings. The equation is-

$$Tc = 0.534Ta + 12.9.$$

The mean outdoor temperature for Monaragala is 30.1°C. Thus, according to the above equation, the comfort temperature for Monaragala should be 28.92°C. The above-mentioned comfort equation proves that higher outdoor conditions will have higher levels of comfort temperatures. Although the required comfort temperature is 28.92°C, the obtained mean operative temperature through measurements indoors is 32.2°C. The investigated operative temperature is 3.3°C more. This proves that the interior spaces are overheated and there is a need to lower the temperature of the indoor spaces with the proper provision of natural ventilation.

4 Conclusion

Tropical urbanization increases the demand for housing and the level of energy demand because it is predicted that half of the world's population will reside in developing nations in Asia and Africa within the next 30 years. The majority of the nation's power users are in the household sector, as seen by the national grid's highest end-user energy demand of 34%. Even though 99.7% of the country is electrified, there are still a few districts that do not have complete electrical accessibility. This study investigates the thermal comfort and energy demand levels of low-income homes in Monaragala's impoverished Grama Niladari divisions. This district contributes 3.2% of the total poverty levels of Sri Lanka.

Findings indicate that 25% of the families in the sample under study fall into this category of being below the poverty line, which is higher than the 23% national estimate. This suggests that a sizable proportion of households experience extreme poverty. Results indicated that the mean electricity consumption is 51 kWh per household month whilst only 25% had access to clean cooking fuels.

Furthermore, findings indicated that the internal spaces are overheated with an operative temperature of 32.2°C and this temperature does not comply with ASHRAE 55 standards. The required comfort temperature, according to the comfort temperature equation is 28.92°C. However, the investigated operative temperature is 3.3°C more. Thus, these findings highlight the importance of implementing a housing approach for low-income houses, prioritizing climate change and the well-being of the occupants in a tropical climate context. This accomplishes the interaction of several United Nations Sustainable Development Goals (SDGs), with six principally significant SDGs such as poverty (1), health (3), infrastructure (9), inequalities (10), cities (11), and climate (13).

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LIFE CYCLE COST ANALYSIS OF GREEN BUILDING PROJECTS IN SRI LANKA

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Abstract: Increasing green construction adoption is at the forefront of the global building industry as society pushes towards greater sustainability. Green building has risen to the top of the priority list for the construction sector as the globe advances towards greater sustainability. While Sri Lanka is now experiencing an energy and economic crisis, green building ideas can support the economy by advancing the building industry. If Sri Lanka adopts the green building concept within the next 30 or 40 years, it might be able to transform revenue-generating prospects in the construction industry. People only take into consideration the construction's initial cost, not the total cost over the course of its whole life. It is preferable to consider a building's Life Cycle Cost (LCC), which includes cost parameters for maintenance, operational and services cost parameters. Therefore, the main objective of this study is to identify the factor that has the most impact on LCC in a green building and to provide solutions to reduce that factor's impact to further reduce LCC. The necessary authorities were surveyed using a questionnaire and interviewed online, allowing for a full analysis of the study. This uses both quantitative and qualitative analysis to validate findings and offer suggestions based on opinions from many parties in the building industry. The services cost was the cost data for LCC that is most affected, according to the studies. Further, this study made suggestions for reducing expenses in sustainable building to ultimately lower LCC. This research study will be relevant for Sri Lanka to address the current economic crises by taking monetary account of the green construction idea.

Keywords: Green Building; LCC; Services cost; Maintenance cost; Operational cost

1. Introduction

The development of green buildings is a crucial strategic move toward attaining sustainable development, energy and resource conservation, and environmental preservation. To encourage the healthy expansion of green buildings, many nations have produced green building grading guidelines (Liu, Guo, and Hu, 2014). According to the World Business Council of Sustainable Development, buildings utilize 40% of the energy consumed worldwide (Geoffrey, Tathagat, and Dod, no date). Numerous studies on sustainable building have been conducted to look at ways to lower the amount of energy used in the construction sector (Tathagat and Dod, 2015). The advantages of economic efficiency the initial cost of green buildings can be reduced due to integrated energy solutions and smaller systems (Waidyasekara and Fernando, 2012). There are considerable advantages to green buildings over non-green structures, according to several research concerning green buildings (Simpeh and Smallwood, 2018). Additionally, lower yearly fuel and electricity expenses because of the decreased need for modern energy systems and peak power, as well as reduced yearly fuel and electricity costs, lower consumer energy prices are the outcomes (Waidyasekara and Fernando, 2012). Sri Lanka is going through a significant economic and energy crisis. The economy of Sri Lanka is collapsing. Green building ideas are currently popular topics since they can help the economy by supporting the building sector. In conventional buildings, most items are destroyed during renovation, but green buildings' features can be used as reusable parts. Before 30 or 40 years, if Sri Lanka adopts a green building concept, there may be a chance to transform this into a revenue-generating possibility for new development. About the present energy crisis, it might be of great assistance (Geoffrey, Tathagat, and Dod, 2015). Building construction typically takes between three and four years. On the other side of the hand, a building's useful life can last 60 to 70 years. There are also additional expenses for upkeep, overhaul, and repairs during a building's lifespan. It's crucial to include both the construction cost and the life-cycle expenses when comparing the expense of a green building with a conventional structure.

The evident economic benefits of green buildings include a shorter time to pay back due to reduced water, energy, and health expenses, as well as a speedier return on investments and increased income. Because green buildings consume less energy and water and can maintain their buildings for less money & they have lower operating costs (Geoffrey, Tathagat, and Dod, 2015; Tathagat and Dod, 2015).

Green buildings cost 37% more to build than conventional ones, but they also cost less to operate, maintain, and demolish, saving 28%, 22%, & and 11%, respectively (Weerasinghe and Ramachandra, 2018). This concept of green construction, however, is not well known in Sri Lanka. They largely employ traditional building techniques because of their inexperience, lack of knowledge, inefficient procurement procedures, and lack of specialists with the necessary training. People just look at the project's beginning costs, not all the costs over its life cycle (Tathagat and Dod, 2015).

A pilot survey was conducted to compare life cycle costs (LCC) be- tween green buildings (university buildings) and non-green buildings (university buildings). The pilot survey's findings indicate that while the initial expense of a green building is more than that of a non-green structure, the green building saves money during its lifetime and is ultimately more advantageous. Then, utilizing sustainable development in the building sector might help Sri Lanka overcome its current energy and economic crises. Therefore, cost reduction through sustainable growth is a significant need now. The LCC is impacted by several things. The primary objective of this study is to determine the element that has the most influence over the LCC in a green building as well as offer ways to mitigate that factor to further lower the LCC.

2. Literature Survey

Building construction typically takes between three and four years. On the other side of the hand, a building's useful life can last 60 to 70 years. There are also additional expenses for upkeep, overhaul, and repairs during a building's lifespan. It's crucial to include both the construction cost and the life-cycle expenses when comparing the expense of a green building with a conventional structure. The entire cost across the asset's useful life is represented as a present value. The initial capital cost, financing costs, operating costs, maintenance costs, and eventual disposal costs for the asset are all included in this. All earnings and losses from the future are transformed into current values by using discounting methods (Goh and Sun, 2016). Initial expenses and recurring expenses for the project were considered in the LCC.

2.1 Initial Cost

Capital expenses like purchasing land, constructing it, remodeling it, and purchasing the instruments required to complete the construction job might all be considered initial costs. Costs include day works, measured works, prime cost total, preambles, and preliminary sums (Fuller, 2006). Studies claim that the high cost of GBs precludes their widespread deployment in many nations. Initial costs for green buildings are 5–10% more than for conventional structures, with greater costs in the dwellings, academic and medical sectors. Green technology adoption by GBs is more expensive and time-consuming, which has created a bottleneck (M.S. Soujanya and H.A.E.C Jayasena, 2018). According to, (Weerasinghe and Ramachandra, 2018). Construction costs for green buildings are 37% more than those for conventional buildings (Weerasinghe and Ramachandra, 2018). Due to a lack of understanding individuals in Sri Lanka only consider the project's initial expenditures rather than all associated costs over its lifespan.

2.2 LCC Cost Items

Each category is advised to contain all pertinent expenses associated with keeping a building throughout its full life cycle, including operating expenses, expenses for maintenance, service expenses, and other expenditures like cleaning costs. These costs are then broken down into more precise cost components (Dwaikat and Ali, 2018).

2.2.1 Maintenance Cost

All activities required to maintain a building's structure and individual parts in a manner that satisfies the minimal performance requirements are referred to as maintenance. It also covers all duties required to safeguard and preserve the building's structure. The overall cost of labor, supplies, and other expenses incurred associated with certain tasks and activities are considered the maintenance cost (Weerasinghe and Ramachandra, 2018). Direct labor, materials, fuel, equipment, and bought services are all included in maintenance expenses. Typically, maintenance expenditures may be divided into smaller categories such as routinely scheduled maintenance, unscheduled maintenance (fixing problems) & and intermittent upkeep (for significant life renovation) (Woodward, 1997).

Although the costs of downtime are reduced by a regular, scheduled, preventative maintenance approach, resources are still utilized for maintenance expenses. The 'run it till it breaks' strategy, on the other side, lowers maintenance costs but increases downtime loss (Woodward, 1997). The ongoing maintenance and renovation of items require money additionally. The amount of money required may need to be spent all at once or in cycles, depending on the kind of structural component and piece of equipment. Building maintenance should not be disregarded and should be done regularly. The expenses of dealing with various problems brought on by delayed maintenance are often substantially higher than the price of regular maintenance (Heralova, 2014).

2.2.2 Operational Cost

Power, cleaning, insurance, management of facilities, and other related charges are included in a building's operating costs. The intensity of consumption, the nature of building activities, climatic conditions, and thermal technical factors all affect electricity costs (Heralova, 2014). Electricity expenses, taxes, rent, insurance coverage, cyclical regulatory costs, sewerage costs, and other operating costs may be included in the operational category according to the International Standard ISO 15686-5:2008 (Weerasinghe and Ramachandra, 2018). As for energy expenses, water expenses should be managed similarly. Water use expenses and water disposal expenses are the two main categories of water expenses (Fuller, 2006). The sewerage price is the sum of a baseline price based on the annual cost of the business property and an excess fee based on average water use above 100 cubic meters (Rybka, Bondar-Nowakowska, and Polonski, 2016). Utilizing water-efficient irrigation, water recycling, and water-efficient appliances are all important for water conservation (Illankoon and Lu, 2019).

In practical applications, it might be difficult to predict energy costs with accuracy during the design phase. It is necessary to make assumptions about the use of layouts, occupancy rates, and schedules since they all influence how much energy is used. Engineering analysis can offer tails on how energy is consumed by a building at the preliminary design stage (Fuller, 2006). Building industry architectural design processes are time-consuming due to issues with unreliable data, difficult software, and modeling techniques. Buildings consume 32% of all energy generated worldwide and produce 19% of all energy-related greenhouse emissions (Doan *et al.*, 2017). 48% of the total cost of the building's life cycle is made up of energy costs, which are more expensive overall than both the building and design costs combined. Reducing energy usage was shown to be the factor that had the greatest impact on reducing the overall life cycle cost (Dwaikat and Ali, 2018).

2.2.3 Services Cost

Building services are essential to any structure, but they play a crucial role in green buildings as they directly contribute to most sustainability deliverables including water consumption, energy consumption, and indoor environment quality. Any sustainable building development and its consultants must carefully examine and optimize building service expenditure, which accounts for a significant portion of the cost (Illankoon and Lu, 2019). Building services fall mainly into three categories, according to the new rules of measurement: drainage systems (above and below the ground), mechanical, electrical, and transportation (Illankoon and Lu, 2019). It is found that, in green building projects, although the customer must initially spend more money on modern technology, doing so results in monthly savings on utility bills when compared to the cost of a traditional structure (Kim, Greene, and Kim, 2014).

3 Research Methodology

It was found that the LCC of green buildings is less than traditional buildings according to the pilot survey conducted as the base for this research study. The study's main goal is to identify the main factor that affects LCC of green building projects and suggestions were made to identify ways to mitigate it to reduce the LCC even more. A questionnaire survey and online interviews were conducted with the relevant authorities which allowed for a thorough evaluation of the search. This is a combination of both quantitative (via questionnaire survey selected by stratified random sampling) and qualitative (via in-interviews selected by purposive sampling) analysis to confirm and make recommendations based on the views of different parties in the construction sector.

3.1 Data Collection Methods

Data was gathered via a Google form that was disseminated via email messages, and messages on WhatsApp, Facebook, and Viber. Experts were given questionnaires to complete to obtain the proper responses to the questions. To rank the various points of view, gathered through "Likert Scale" (Kawmudi *et al.*, 2021). A total of 50 close-ended questionnaires were sent (selected through stratified random sampling), & achieved 83.3% of respondents, including engineers, architects, project managers, quantity surveying professionals, and contractors. A purposive sample was chosen since the semi-structured interviews' objective is to choose people with more expertise and practical experience in the study's topic. Quantity surveyors, architects, engineers, contractors, project managers, and other professionals with experience in the construction of green buildings were among the professions that were covered by the interviews.

3.2 Data Analysis Methods

Utilizing Relative Important Index (RII) analysis, which expresses the frequency of the factors that present challenges, the data collected through questionnaire surveys was analyzed. building sector in Sri Lanka. Information acquired from the interviews was analyzed using content analysis.

$$RII = \frac{\Sigma^{5}_{i=1} W_i \times X_i}{A \times \Sigma^{5}_{i=1} X_i}$$

Eq. (1): Relative Important Index Source: (Gündüz, Nielsen and Özdemir, 2013)

Wi-The weight that is allocated for each factor. Xi-Number of responses
A-Highest weight

On a scale of 1 to 5, the main elements were recognized as highly agree, agree, moderately agree, mildly disagree, and strongly disagree. Tables and graphs were used for the presentation. For ease of comprehension, the elements were identified independently using a cording technique.

4 Data Analysis

The development of green buildings is a complicated task that requires the assistance of numerous parties with specialized knowledge in various fields. Therefore, discussing the experience regarding the target population's tradesis crucial.

4.1 Background Findings

The broad perspective of respondents, including their occupation and industry experience, was evaluated because, depending on the viewpoint of different persons, the replies to the problems may vary according to their knowledge and thinking abilities.

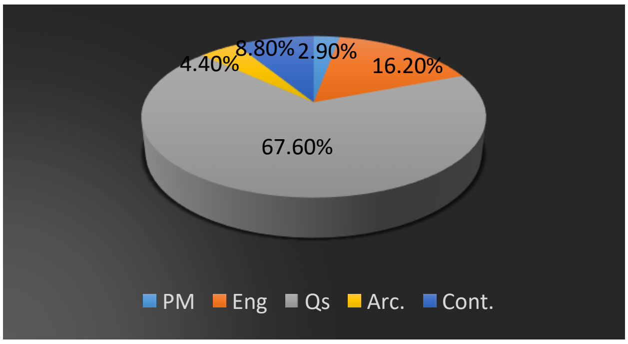

Figure 1: Respondents based on Profession.

Subsequently determined whether the professionals had experience with working on green buildings.

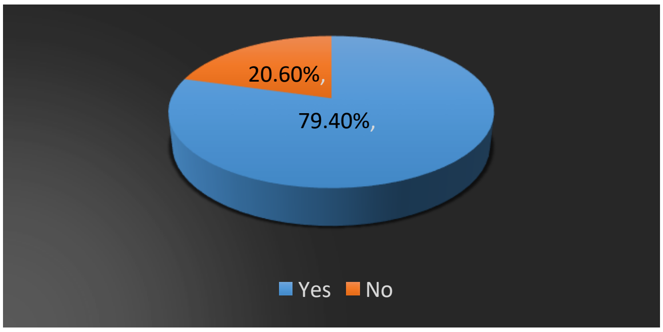

Figure 2: Experience of the professionals in GBs.

According to Figure 2 over 70% of respondents said they had experience working in the field of green building construction. Then find out to gatherthe data on their experience in green buildings. The bulk of respondents, or 50%, had expertise with green buildings for five to ten years, and only 1.5% of experts had experience for more than fifteen years. A trustworthy random sample of construction industry personnel was then used to distribute questionnaires.

4.2 Rank the Main LCC-Related Items

The study identifies three significant LCC-related cost factors for GB building in Sri Lanka. The literature survey identifies the LCC-related cost items,and 12 of them are designated to rank depending on the relative importance of their influence. The respondents' levels of agreement were used to calculate the Relative Important Index. The respondents' survey responses were considered to determine their overall ratings for each factor. As shown in the below-tabulated forms, the criteria were determined using a coding schemefor quick identification and ranking.

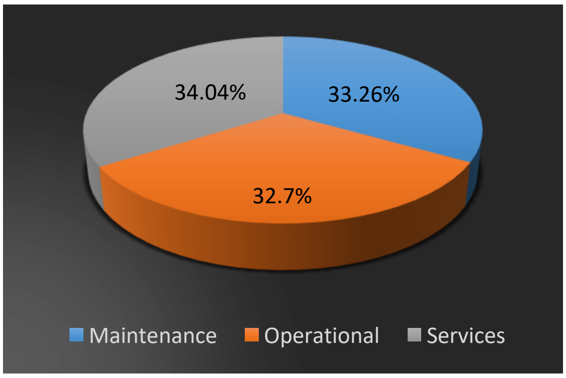

Figure 3: LCC Parameters.

For GB buildings in Sri Lanka, the study highlights three important LCC-related cost aspects: maintenance, operational, and services. The service cost is the greatest LCC parameter discovered, and the operational cost is a minimum LCC parameter, according to the computation resulting from the Relative Important Index.

4.2.1 Maintenance Cost

Table 1: Ranked the maintenance cost items in GB construction according to the RII.

Code	Causes of LCC	RII	Rank
M4	Based on system requirements, maintenance needs for building service components will be decided. The LCC will then benefit long-term from modifying the building services system at the design stage.	0.741	1
M3	The expenses of dealing with various problems brought on by delayedmaintenance are often substantially higher than the price of regular maintenance.	0.729	2
M1	Selecting elements in the design stage with proper structural componentswill reduce LCC in the long term.	0.724	3
M2	LCC may be reduced over time by making element selections throughoutthe design phase with the appropriate equipment.	0.715	4

Based on system requirements, maintenance requirements for construction service components will be determined, and the LCC will then profit long-term from adjusting the building service system at the design stage (M4), according to Table 1. This item was ranked first in the LCC's maintenance cost list. According to the needs of the system, the maintenance requirements for each component of the construction service might vary (Illankoonand Lu, 2019). The second highest-ranking LCC item in terms of maintenance costs was: The costs of addressing different issues brought on by postponed maintenance are frequently significantly higher than the cost of routine maintenance(M3). A building's routine upkeep is crucial and shouldn't be disregarded. The expense of dealing with various problems brought on by neglected maintenance is typically substantially higher than the cost of routine maintenance (Heralova, 2014). LCC may be lowered as time passes by making component selections during the design stage with suitable equipment, according to the item with the lowest rank in the maintenance cost (M2).

4.2.2 Operational Cost

Table 2: Ranked the operational cost items in GB construction according tothe RII.

Code	Causes of LCC	RII	Rank
O4	Even though the initial cost of a solar system increases, it will decreasefuture bills and be advantageous for saving LCC in the long term.	0.785	1
O5	It may reduce long-term power expenses by altering the design earlyin the project, allowing more daylight to enter the structure's interior.	0.762	2
O6	Adopting water reuse techniques (ex: stormwater harvesting systems,rainfall harvesting systems) will minimize the LCC in the long run.	0.741	3
O2	The operational cost of electricity usage will differ due to differentclimatic conditions.	0.732	4
O3	System usage will be reduced by changing the type of the system,which will decrease LCC in the long term.	0.715	5
O1	The nature of the building activities will affect the electricity cost inthe long term.	0.703	6

Even if the initial expenditure of a solar energy system grows, it will lower future costs and be beneficial for saving LCC over the long run, according to the LCC item with the highest operating cost rank (O4). According to theLCC of the brought forward solar panel system, using solar panels with a minimal capacity would result in energy cost savings of 4%, while utilizing solar panels with the required capacity will result in energy cost savings of 54%. For residential structures, solar panels constitute an energy-efficient technique (Illankoon and Lu, 2019). Reducing long-term electricity costs bymaking design changes early stage was accomplished; enabling more daylight to reach the inside of the structure was the second-highest operating cost item that can be used to reduce LCC in the long term(O5). The nature of the construction activities will have a long-term impact on power costs, making electricity the least impacted operational cost category (O1).

4.2.3 Services Cost

Table 3: Ranked the services cost items in GB construction according to theRII.

Code	Causes of LCC	RII	Rank
S2	Adding design alternatives for natural ventilation in the design stage will reduce LCC in the long term.	0.759	1
S1	The LCC will be reduced over time by adjustments to the specific typeof HVAC system.	0.747	2

The most impacted service cost item was determined to be the addition of design possibilities for natural airflow in the design stage, which will crease LCC over time (S2). The LCC analysis may be used for choosing design alternatives and alternative building components including roofing, windows, and building envelope (Heralova, 2014). By making modifications to the kind of HVAC system, the LCC will eventually decline and wasdetermined to be the service cost type that was least impacted (S1). Depending on the energy usage, the expense of energy is distributed across several systems. HVAC system accounts for 48% of this cost/saving. Credit for peakpower demand reduction has a direct impact on the building's HVAC system(Illankoon and Lu, 2019).

Interviewees 1 and 4 stated that "*There are additional expenditures forservices that have an impact on the LCC, such as those for heating systems,security systems, telecommunications, and other connected expenses*". The operational costs of a green building, such as cleaning, management of the facility, insurance, and sanitary expenditures, are higher, according to interviewees 2 and 3. Interviewee 5 further mentioned other costs that affect the LCC, such as irrigation cost criteria. According to the interviewees, by usingenergy-efficient equipment such as LED bulbs, LCC can reduce operationalcosts in the long term. And LCC depends on electricity, HVAC, and heating systems. Then, when implementing those systems in a building, it is important to consider LCC. Green architectures further explain that throughout the design changes in the design stage, LCC can be reduced by adding alternative structural components such as more windows to get more natural ventilation and natural lighting. The respondents claim that there are problems with controlling recurrent costs, including problems with the law, inadequate planning, bad maintenance, and an inadequate degree of awareness about constructing alternatives, which can lower LCC in the long run.

5 Conclusion

The construction industry has established green building as its foremost objective as the globe advances toward greater sustainability. Despite the economic and energy crises, Sri Lanka is now experiencing, the growth in the construction industry is because of the principal application of green construction. Through the pilot study, it was discovered that the maintenance, operational, and service cost parameters are the key three cost factorsthat have a long-term impact on LCC. There have been studies done in the past that focus on LCC factors in green buildings. However, the long-term impact of cost parameters on the LCC is still being determined. This study considers the influence of LCC factors on a green building that decreases LCC in the long term. Data from green professionals in Sri Lanka were gathered using Google Forms, questionnaires, and semi-structured interviews. The Relative Important Index (RII) was used to evaluate the data to determine the long-term impact of cost items on LCC. To facilitate rapididentification and ranking, the criteria were established using a coding system. The services cost was the cost data for LCC that is most affected, according to the studies. Further, this study made suggestions for reducing expenses in sustainable building to ultimately lower LCC.

6 Recommendations

Green industry experts offer a list of suggestions for lowering LCC's ongoing expenses through this study.

6.1 Recommendations to lower the maintenance cost.

- Maintain the real green building criteria with routine maintenance.
- Choose components with the appropriate structural aspects throughout the design phase.
- Choose elements throughout the design process using the rightequipment.
- To decrease maintenance, modernize building services.
- Utilize prefabricated materials and green-certified materials.

6.2 Recommendations to lower the operational cost.

- Use sustainable elements like photovoltaic (PV) panels, solar tubes, eco-roofs, LED (light-emitted diode) lighting, and rainwater recycling technology.
- Create stormwater harvesting systems, systems for ventilation, natural lighting systems, documented energy usage, thermal transfer, and a power calculation plan.
- Use recycled wastewater and employ water treatment techniques to conserve it.
- Use solar systems to reduce electricity bills and reduce LCC costsin the long term.
- Using alternative structural elements, such as larger windows, it is possible to increase natural ventilation and lighting and it will reduce energy usage of the building.

6.3 Recommendations to lower the service cost.

- LCC should be calculated while installing HVAC systems within abuilding.
- Maintain environmental and construction-related legislative signs, green building principles should be used in the planning process.
- Energy savings should be aided by more insulation in the walls, ceilings, and flooring.
- Utilize contemporary technologies for services. As an illustration, security systems.

Perform further study on this topic to advance the industry's methods. Consequently, recurrent expenses as well as LCC may be decreased over time by utilizing the concepts and alternative design methodologies in the designstage according to the green professionals in Sri Lanka.

Acknowledgment

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FLEXURAL BEHAVIOUR OF REINFORCED RUBBERIZED CONCRETE BEAM

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Abstract: The utilization of discarded tires as aggregate for concrete can reduce environmental pollution, and their usage as raw materials, leads to sustainable development and efficient economic growth. The majority of research studies have been focused on the development of rubber-based concrete for non-structural applications. Even though few research studies have shown the suitability of rubberized concrete for structural purposes, none of them have assessed the feasibility of structural applications. In series of four-point bending tests were conducted to investigate the behaviour of reinforced rubberized concrete beams under flexure. The results indicate a reduction of 23.07% and 12.5% in moment capacity and workability and increment of deflection compared to normal reinforced concrete beams. The results showed that the compressive strength and splitting tensile strength of the concrete matrix were significantly reduced by 35.5% and 53% with the inclusion of the rubber aggregates. The SEM results showed that the presence of rubber particles in the concrete matrix increased porosity and decreased microstructural compactness, leading to weaker interfacial bonding between rubber particles and the cement paste. However, it exhibited 32.66% higher flexural toughness, indicating its ability to absorb and dissipate energy.

Keywords: Rubberized concrete; Flexural strength; Cyclic load response; Load-deflection

1 Introduction

The disposal of rubber into the environment has created major issues in terms of health, environment, and economics in the world. The production of tires worldwide is projected to be 1.5 billion per year (Shen et al., 2013). Among them, every year 1 billion tires approach the end of their service life, and more than half of them are dumped in the environment without any treatment (Azevedo et al., 2012). Those discarded tires are disposed of by landfilling, burning, using them as fuel, producing carbon black, etc. If landfilling is done, breeding habitats for mosquitos and various pests have been created due to storing water for a long time in tires. Tire burning causes serious fire hazards, temperature rises, and accumulation of harmful toxic gases in the atmosphere. Quality petroleum products can also not be produced using rubbers (Thomas and Gupta, 2016). Therefore, people looked for an effective way to stop further destruction caused by these discarded rubbers. At present the construction industry has restored to use of environmentally friendly raw materials or concrete made from solid waste as aggregate to maintain sustainability of production activities. Rubberized concrete is one of the possible solutions for the use of discarded rubber which is made by replacing some kind of natural aggregates from the rubber aggregates. It is an environmentally friendly attempt and economically viable because it can be replaced with high-cost natural aggregates resulting in a low impact on the environment and future problems of scarcity of natural resources.

As a result, in the last 30 years, many researchers investigated the behavior, properties, strength development methods, and various possible applications of rubberized concrete. When comparing the properties of rubberized concrete, it has a significant decrease in strength (compressive strength, Modulus of elasticity, splitting tensile strength) and stiffness of concrete after mixing discarded rubber tire particles (Miller and Tehrani, 2017). However, the compressive strength and tensile strength of rubberized concrete decrease significantly when using coarse rubber aggregates instead of fine rubber (BekirTopçu, 1995). On the positive side, rubberized concrete improves the durability, deformability, ductility, and impact resistance of concrete. Researchers have attempted to explore strength development methods for rubberized concrete to avoid these negative impacts. Silica Fume is one of the effective strength development methods of rubberized concrete because it increases adherence between the cement mixture and rubber particles and improves the compressive strength of rubberized concrete (Gesoğlu and Güneyisi, 2007). Also, compressive strength, the modulus of rupture, splitting tensile strength, moment capacity, and failure load of rubberized concrete can be increased by using steel fibers (Eisa, Elshazli, and Nawar, 2020). Surface treatment of rubber particles is an effective method to avoid the low modulus of elasticity and hydrophilicity which caused the decrease in the strength of rubberized concrete. (Ghedan and Hamza, 2011). However, the strength of interfacial adhesion between the cement mixture and the rubber particles can be enhanced by utilizing surface treatment of rubber particles (Jiang et al., 2021).

The researchers have developed low and medium-grade rubberized concrete and ensured its performance in non-structural applications. However, the products developed so far have indicated non-suitability for structural applications. The current researchers at the University of Moratuwa have successfully developed this product to overcome such problems in structural applications. As a continuation of this research, the assessment of the flexural behavior of reinforced concrete rubberized beams was investigated and presented in this paper.

2. Overview of the Test Program

2.1 Materials

Fine aggregate, sourced from river-washed sand with a fineness modulus of 2.75 and a size range of 0-5 mm, was employed in the experiment. Additionally, coarse aggregate in the form of washed gravel was utilized, available in two sizes: 5-10 mm and 10-20 mm. Portland cement (CEM I) with a strength class of 42.5MPa was the chosen cement. A superplasticizer was added to improve the workability.

The rubber particles used in the research were obtained from discarded vehicle tires, which underwent mechanical shredding at a rubber recycling factory. These rubber particles were then categorized into three different sizes: fine rubber particles (0-5 mm) were used as a substitute for the fine aggregate, while coarse rubber particles (5-10 mm) and larger rubber particles (10-20 mm) replaced the gravel. The separation of rubber particles is shown in Figure 1.

(a) (b) (c)

Figure 1: Rubber particle sizes (a) 10-20mm, (b) 5-10mm, (c) 0-5mm.

1.1 Mix Design

(Arachchi, Gamage and Selvaranjan, 2022) have conducted a detailed investigation on developing rubberized concrete for structural applications and the mixture with optimum performance was selected for the current investigation.

Table 1: Mix Design

Material	Quantity (kg/m^3)	Material	Quantity (kg/m^3)
Cement	340	**Coarse aggregate (5-10 mm)**	364
Silica fume	42.5	**Coarse aggregate (10-20 mm)**	637
Fly ash	42.5	**Water**	150
Fine aggregate (0-5 mm)	820	**superplasticizer**	7.66

2 Results and Analysis

2.1 Compressive Strength Test

A total of 6 concrete cubes, size 150 mm × 150 times 150mm were subjected to loading at a consistent rate of 0.6MPa/Min. These samples contain two cubes each from rubberized concrete with pre-treatment, rubberized concrete without pre-treatment, and normal concrete. All the samples were kept curing under the same conditions. Then, 28 days of compressive strength was determined by (BS EN 12390-3, 2019).

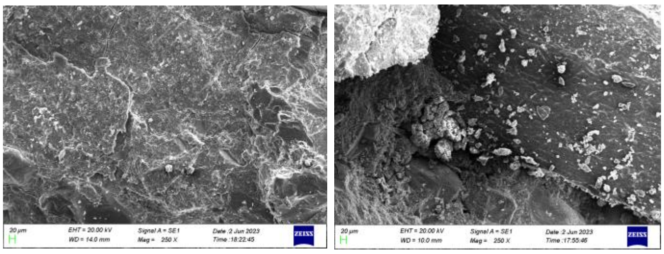
The compressive strength of rubberized concrete has reduced by 35.5% and 42.58% in pre-treated and non-pre-treated samples, respectively compared to normal concrete. This might be due to the weak bonding between rubber particles and cement paste and the higher stiffness of sand particles compared to rubber particles (Eisa, Elshazli, and Nawar, 2020). The RuC specimens exhibited a similar failure pattern [Figure 2], with failure initiation either from the top or bottom layer. This can be attributed to the upward movement of rubber aggregate towards the top layer of the concrete due to its low specific gravity. The average 28-day compressive strength was 62.7 MPa, 40.45 MPa, and 36 MPa for normal concrete, pre-treated rubberized concrete, and non-pre-treated rubberized concrete samples respectively.

Figure 2: Observed failure patterns of rubberized concrete samples.

2.2 Scanning Electron Microscopy Analysis

The test, by the (ASTM C1723-16, 2022) standard, was carried out. The objective was to compare the particle size, shape, and porous nature of rubberized concrete and normal concrete samples. The SEM test was conducted using ZEISS® EVO 18 Analytical Research SEM. The SEM images utilized in this study were magnified 250 times to facilitate detailed examination.

Figure 3(a) and Figure 3(b) show SEM micrographs of normal concrete and rubberized concrete mixtures respectively. The presence of rubber in the concrete mixture has noticeable effects on the microstructure and mechanical properties. As shown in rubberized concrete sample has a considerable size of pores within the matrix, resulting in decreased microstructural compactness compared to the normal concrete sample. It will be caused to weaken the interface between the rubber particles and the cement matrix. It will contribute to reducing compressive strength, load-bearing ability, and overall strength of RuC samples.



(a) (b)

Figure 3: Microscopic images of the matrix of the concrete specimens (a) without rubber and (b) with rubber.

2.3 Water Absorption

By (ASTM C642, 2021) standards, the water absorption test was conducted by casting 100mm by 200mm cylinders for both normal concrete and rubberized concrete. This test was conducted to check whether durability properties of rubberized concrete concerning the normal concrete. According to Table 2, the water absorption of the RuC (7.55%) is higher than the NC (3.49%) sample. This is mainly due to the porosity of the RuC that the voids act as pathways for water to penetrate the concrete more easily, increasing its water absorption capacity.

Table 2: Results of water absorption

Concrete Type	Water Absorption (%)
RuC	7.55
NC	3.49

2.4 Splitting Tensile Strength

By (ASTM C496/C496M, 2017) standard, the splitting tensile strength test was conducted by casting 150mm by 300m cylinders. The specimens were subjected to the load using two hydraulic jacks of 1000 kN capacity, applying continuously and without shock, at a constant rate of 50 kN/min as shown in Figure *4*.

Figure 4: Splitting tensile test setup.

The measured average tensile strengths of RuC and NC were 1.7 MPa and 3.5 MPa, respectively. This indicates a 51.43% reduction in RuC when compared with NC. The decrease in splitting tensile strength observed when utilizing rubber aggregates in the concrete can be attributed to the limited bond strength between the rubber particles and the cement paste. Figure 5 shows the failure mode of the samples after splitting the tensile strength test.

(a) (b)

Figure 5: After the failure of cylinders (a) NC, (b) RuC.

2.5 Beam testing

A total of six medium-scale beams with a cross-section of 130 mm $times$80 mm and a length of 1650 mm were tested. Out of them, 4 beams were from rubberized concrete and the remaining were from normal concrete as control beams. A typical reinforcement arrangement is shown in Figure 6.

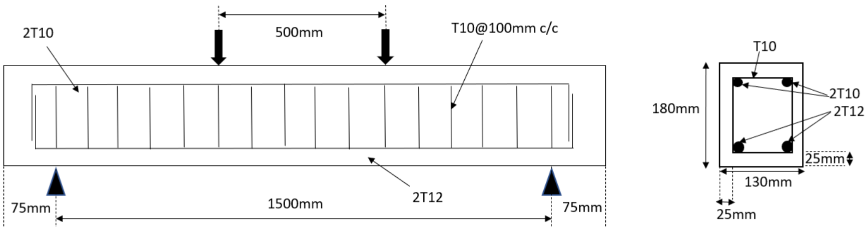


Figure 6: Reinforcement arrangement.

2.5.1 Flexural strength

The beams were subjected to four-point bending tests (ASTM C78/C78M, 2022), with a clear span of 1500 mm under simply supported conditions [Figure 7]. For loading the beams, a hydraulic jack with a maximum capacity of 1000 kN was employed, applying a loading rate of 2 kN/min. Deflection measurements at the mid-span were obtained using a Linear Variable Displacement Transducer (LVDT). To capture the data, both the LVDT and load cell were connected to a data logger, recording the readings corresponding to the incremental load. A crack width ruler was used to measure the crack width.

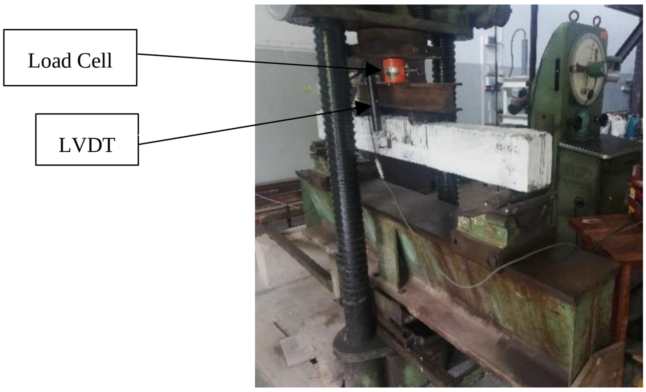


Figure 7: Test setup.

2.5.2 Comparison of test results

The summary of measured data of beam samples is listed in Table 3. The dry density is reduced of RuC mixtures compared to the normal concrete. Concerning the control sample, 7.44%, 7.44%, 7.17%, and 5.75% reductions appeared in RCB1, RCB2, RCB3, and RCB4 beams concrete mixtures, respectively. The reduction in compressive strength is relatively small due to the utilization of well-graded rubber particles.

Table 3: Beam Test Results and Material Properties

Beam No	Unit weight (Kg/m3)	Slump (mm)	Compressive strength after 28 days (MPa)	Load at 0.3mm crack (kN)	Flexural capacity at 0.3mm crack (MPa)
RCB1	2400	170	39.8	15.364	5.47
RCB2	2400	165	39.15	17.869	6.36
RCB3	2407	185	42.3	22.044	7.85
RCB4	2444	180	40.9	18.704	6.66
NCB5	2593	200	57.1	24.048	8.56

It is observed that the workability of concrete is decreased with the inclusion of rubber aggregates. Concerning the normal concrete mixture, 15%, 17.5%, 7.5%, and 10% reductions were noted in RCB1, RCB2, RCB3, and RCB4 beams concrete mixtures, respectively. According to Figure 8, a normal concrete beam has a high load capacity compared to rubberized concrete beams. The load application procedure for RCB3 and RCB4 beams differs, as load cycles are initially applied, followed by a transient load applied until a 0.3 mm wide crack initiation. This simulates the service life of structural elements subjected to cyclic loading. This sequential loading approach results in a 22.65% higher load capacity for these beams compared to RCB1 and RCB2 which were subjected to transient load only.

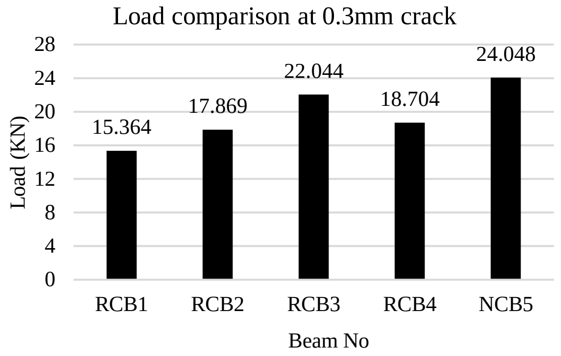


Figure 8: Load at 0.3 mm crack initiation.

Rubber particles in the concrete matrix serve as energy-absorbing entities. They deform easily and dissipate energy when subjected to external loads, resulting in increased ductility, greater deflection, improved deformability, and enhanced flexibility in the rubberized concrete beams. That phenomenon is verified in this investigation. As shown in Figure 9, there is a high deflection variation appears in RuC beams compared to the control sample. All three beams have permanent displacement after the unloading. However permanent displacement is increased in RuC compared to the NC sample. Specifically, RCB1 and RCB2 show a 632% and 240% increment, respectively, in permanent displacement when a 0.3mm crack appears, relative to the NC sample.

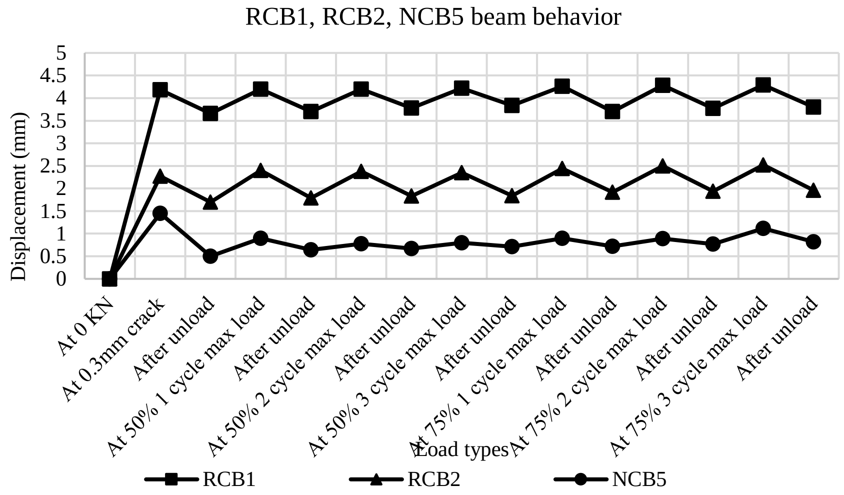


Figure 9: Deflection behavior of RCB1, RCB2 & NCB5.

The deflection of beams RCB1 and RCB2 was found to be higher when subjected to 50% and 75% cycles of maximum loads compared to the deflection observed when a 0.3 mm crack occurred. After unloading, the permanent displacement at 50% and 75% load cycles are higher than the 0.3 mm crack load cycle. The reason for this is that when loading the beams until a 0.3 mm crack occurs, a certain load level induces plastic deformation, after which the deflection continues to increase. As shown in Figure 10, the deflection observed at 50% and 75% of the maximum load cycles is lower in beams RCB3 and RCB4 compared to the corresponding deflection at 0.3 mm crack initiation. This can be attributed to the fact that the load cycles were initially applied to those beams, gradually increasing the load, which resulted in reduced deflection compared to the latter at a 0.3 mm wide crack.

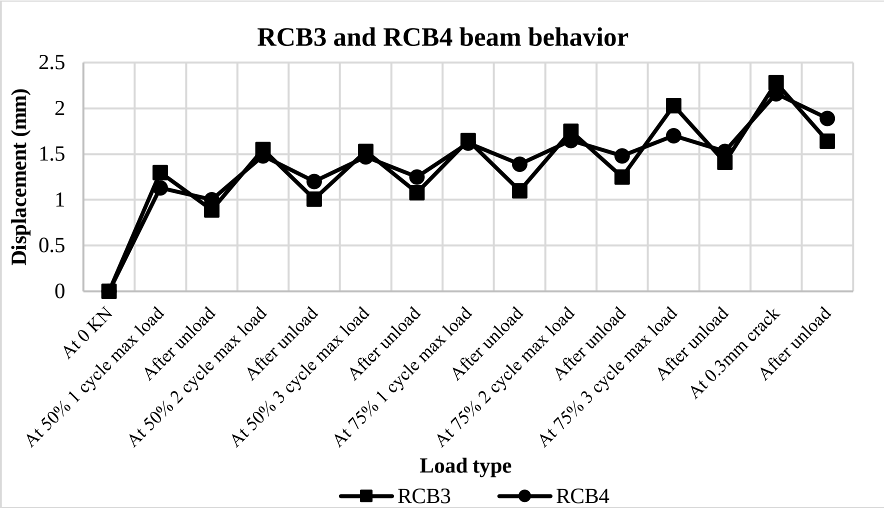


Figure 10: Deflection behavior of RCB3 & RCB4.

The calculation of flexural toughness typically involves determining the area under the load-deflection curve obtained from the flexural test. Rubberized concrete samples have higher flexural toughness compared to the normal concrete sample. Concerning the control sample, 49.96% and 15.36% increments are experienced in RCB1 and RCB2 beams because RuC can absorb and dissipate the energy.

3 Conclusions

This paper explores the properties of rubberized concrete and examines the flexural behavior of reinforced rubberized concrete beams. The results of this research led to the following conclusions:

- Rubberized concrete samples, both with and without pre-treatment, showed reduced compressive strength compared to normal concrete, with reductions ranging from 35.5 % to 42.6 %.
- SEM analysis revealed that the presence of rubber particles in the concrete matrix increased porosity and decreased microstructural compactness, leading to weaker interfacial bonding between rubber particles and the cement matrix.
- Rubberized concrete exhibited higher water absorption compared to normal concrete with an increment of 116.3% when compared with normal concrete due to its higher porosity and the presence of voids, allowing water to penetrate more easily
- Splitting tensile strength tests demonstrated a 53 % decrease in the strength of rubberized concrete mixes compared to normal concrete, primarily attributed to the limited bond strength between rubber particles and the cement paste.
- Flexural tests showed that rubberized concrete had lower load capacity, and reduced workability with reductions of 23.07 % and 12.5 %, respectively, compared to normal concrete
- Flexural test shows that rubberized concrete beams had higher deflections compared to normal concrete and also recovered after unloading
- However, Rubberized concrete exhibited higher flexural toughness with an increment of 32.7 % compared to normal concrete, indicating its ability to absorb and dissipate energy

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FRAMEWORK TO DECIDE ON THE APPROPRIATENESS OF RECYCLED CONCRETE AGGREGATES AS A CONSTRUCTION MATERIAL IN DIFFERENT CONSTRUCTION PROJECTS IN SRI LANKA: WITH AN INSIGHT INTO THE COST-BENEFIT ANALYSIS

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Abstract: Discarded concrete directly accounts for about 50% of the overall construction and demolition waste. Enormous pollution and energy consumption during concrete production, together with rising demand for concrete, pose a constant danger to environmental sustainability and human health. Since zero waste and zero pollution are hard to achieve in the construction industry, numerous studies on concrete recycling technologies and benefit assessments have been carried out over the past several decades. The attempts to find ways of dealing with discarded concrete is one of the tasks aligned towards the aforementioned goal. As the construction industry pushes towards sustainability, raw material substitutions such as Recycled Concrete Aggregate (RCA) have great potential to mitigate the negative consequences of concrete while maintaining engineering capabilities. However, the concept is yet to be implemented effectively and commercial scale in Sri Lankan construction practices. Inadequate knowledge, lack of technology, and the absence of a proper framework may be the primary causes of that. To optimize utilization while achieving economic, environmental, and social benefits, all the costs and benefits should be addressed to arrive at an objective decision. Therefore, this study mainly focused on developing a framework to assess the appropriateness of utilizing reclaimed concrete aggregates in different construction projects in Sri Lanka. The study anticipated a mixed methodology that includes eight (08) expert interviews and a questionnaire survey. Through the manual content analysis, the process of recycled concrete aggregate production and all the related cost and benefit centers were identified. The findings were ranked based on the significant impact. Finally, a framework is presented as a guideline to decide on the appropriateness of recycled concrete aggregates in place of natural aggregates in a construction project in Sri Lanka.

Keywords: Construction and demolition waste; Cost-benefit centers; Framework; Natural aggregates; Recycled concrete aggregates

1. Introduction

The management of waste from construction and demolition has become one of the primary issues that have arisen in the construction industry. Usually, all the debris generated during the construction, renovation, and demolition of structures is defined as "construction and demolition waste." Buildings and structures produce waste throughout their entire lifecycle and according to Tam, (2008) among all waste, discarded concrete directly accounts for about 50% of total waste generation. This discarded concrete used to be routinely transported to landfills for disposal, but in this era of increased environmental consciousness, tougher environmental regulations, and the need to keep construction costs low, concrete recycling has numerous benefits that have made it a more appealing option.

Even though numerous studies by Ma et al., (2022), Wagih et al., (2013), and Begum et al., (2006) have been carried out on concrete reclamation methods, procedures, barriers, and cost-benefit analyses, consumers are often hesitant to purchase recycled materials on the assumption that it may pose a greater amount of functional risk because the evaluation of the properties and performance of materials, economic and environmental benefits separately do not converge to provide a clear answer; to determine the appropriateness of the material. Nevertheless, a gap exists in the literature since the developed studies do not embody a framework, which consists of all associated cost, and benefit centers. Moreover, considering the construction industry's research trend on recycling concrete waste, Rao, Jha and Misra, (2007) emphasized that studies should be oriented toward developing frameworks to decide on the appropriateness of utilizing recycled material in construction. Additionally, the primary cause of the limitations of existing applications of recycled concrete aggregates is a lack of appropriate technology and the absence of a proper framework. Even though the concept of concrete recycling is not novel to the industry, an industrial gap exists to address the appropriateness of utilizing reclaimed concrete aggregates within construction projects to achieve benefits. Therefore, it is essential to develop a framework to decide on the appropriateness of recycled concrete aggregates as a construction material, to address the research gap based on the existing literature and the industrial requirement. Before using recycled materials for a construction project, it is critical to determine whether they will provide economic, and environmental benefits and result in profitable projects while providing solutions to reduce waste. Consequently, the study aimed to propose a framework to decide on the appropriateness of recycled concrete as a recycled material in the Sri Lankan construction industry.

2. Literature Review

2.1 Concrete waste in the world

Etxeberria et al., (2007) defined concrete as the most widely utilized building materials in the industry and no construction project is currently feasible without using concrete. Supporting this and with the addition of facts, (Nilesh Kurjibhai Vasoya & Harishkumar R Varia, 2015) implied that, this is primarily due to its high strength, workability, and durability. As per the statistics, the global annual production of concrete exceeds 25 billion tons (Feng et al., 2022). As mentioned by Tam, (2008) concrete waste directly accounts for about 50% of all waste generated among different types of materials. Accordingly, in both economically developing and developed countries, it has become a major environmental concern (Mohammed et al., 2022). Moreover, Suocheng, Tong, and Yuping, (2001) showed approximately 70 million tons of C&D waste and soil were reported to be wasted annually in the UK, and construction activities account for nearly 40% of China's annual production of municipal solid waste. Similar to other developed nations, Liang et al., (2015) stated that the US generates about 30 million tons of concrete debris annually. Moreover, as a result of excessive use of materials, the waste of concrete and mortar in Sri Lanka showed 21% and 25%, respectively (Rameezdeen et al., 2004).

2.2 Adaptation of Concrete Waste Recycling

According to Tam, Soomro, and Evangelista, (2018), the global aggregate production nearly doubled from 21 billion tons to 40 billion tons from 2007 to 2014. Also, to reduce the harmful impacts of the disposal of concrete waste, construction projects should be preceded by rigorous deliberation (Kamali et al., 2019). As mentioned by (Yuan & Shen, 2011) concrete waste cannot be avoided, and "zero waste" is impractical, various studies have been conducted over the recent decades to find ways to reduce the production of waste in the construction industry. However Peng, Scorpio, and Kibert, (1997) suggested that recycling strategies should be considered if the waste generated cannot be reused without the recycling process. Collectively Xiao et al., (2012) and Ma et al., (2022) stated that recycling discarded concrete and producing an alternative aggregate for structural concrete is the best solution to challenges such as a growing shortage of virgin aggregate and negative environmental impact and landfill space scarcity.

2.3 Recycled concrete aggregates and natural aggregates.

As mentioned by (Estanqueiro et al., 2018) natural or recycled aggregates account for approximately 70% of the volume of concrete, and therefore a large amount of aggregates has to be produced worldwide. Collectively (Xiao et al., 2012) stated that the need to recycle waste concrete as natural aggregate in new concrete has been driven by the challenges associated with disposing of concrete rubble and demolition waste, as well as a growing shortage of virgin aggregate. According to Etxeberria et al., (2007), the primary concern with utilizing recycled concrete aggregates in fresh concrete is the presence of adhering mortar, which is the key distinction between RCAs and natural aggregates.

Varma & Kalamdhad, (2018) stated that recycling is reprocessing of a previously used material into a new material or use. According to Sarvut et al., (2018) recycled concrete aggregate is typically produced through the crushing of concrete waste, screening, and the removal of reinforcement, wood, plastics, etc. Musa and Wang, (2013) implied that the majority of recycling plants use both primary and secondary crushers and typically, the primary crusher crushes the material to 60-80 mm before feeding it to a secondary crusher. Following secondary crushing, the material then passes via two screens to sort into aggregate larger than 19 mm, within 19 mm and 7 mm, and less than 7 mm (and used as road metal). After that, the material larger than 19 mm is fed back into the secondary crusher, and the 7-19 mm portion is screened to produce coarse aggregate by NZS 3121:198615 grading requirements.

In contrast to the RCA, Langer, (2001) stated that natural aggregates are particles that have been derived from natural deposits like sandpits or quarries. According to Estanqueiro et al., (2018), in the life cycle of natural aggregate production, there are four main phases; exploration, extraction, processing, and transportation. Langer, (2001) implied that establishing a new quarry is a time-consuming, expensive process that may involve a significant expenditure and therefore aggregate production to be economically viable, all costs must be covered, including acquisition, operation, regulatory compliance, and landfill. Moreover Wilburn and Goonan, (1998) stated that mining involves continuous monitoring and rehabilitation, and also costs associated with exploration, permitting, overburden clearing, preparation of quarry, and ongoing and final site reclamation must be considered. In addition, blasting necessitates the use of explosives and heavy machinery, which can hurt the environment (Estanqueiro et al., 2018). Furthermore, Ohemeng and Ekolu, (2020) emphasized that quarry operations as well can have detrimental effects on the environment in many different ways.

2.4 Feasibility of utilizing recycled concrete aggregates

Estanqueiro et al., (2018) identified that environmental impact assessment, strategic environmental assessment, life cycle analysis, risk assessment, cost-effectiveness analysis, multi-criteria analysis, and cost-benefit analysis are frequently used to evaluate the feasibility of alternative building materials but among these tools evaluating cost-benefit analysis is very critical to decide on the appropriateness of recycled material as it evaluates costs and benefits from both "economic" and "financial" perspectives (e.g., societal benefit, cost and also revenues and costs to investors). As mentioned by (Begum et al., 2006), typically economic feasibility is measured by using standard processes of assessments for net benefit such as cost-benefit analysis.

According to Begum et al., (2006) all costs and benefits must be addressed when completing a cost-benefit analysis of recycling-generated waste benefits include all direct, indirect, and intangible benefits like conserving landfills and the expenses of all direct, indirect, and intangible costs associated with recycling. In a review of the cost-benefit analysis of on-site recycling of demolition debris, Begum et al., (2006) identified the following cost components: collection costs of discarded materials, separation, Equipment, labor, and transportation cost. Limbachiya, Leelawat, and Dhir, (2000) indicated that coarse recycled aggregates can be used in a variety of high-strength concrete mixes with acceptable engineering properties such as compressive and flexural strength, porosity, modulus of elasticity. Moreover Ma et al., (2022) argued that analyzing the use of admixtures, water-to-cement ratio, use of supplementary cementitious materials, and water absorption is crucial before the selection of RCA for the project. Furthermore, environmental concerns like energy consumption, and CO2 emissions occur during the production, construction, usage, and disposal phases of the recycled concrete life cycle because Quattrone, Angulo, and John, (2014) mention that the energy consumption for transporting and using heavy machinery for preparation of RC is a significant contributor to CO2 emissions from recycled concrete.

3. Research Methodology

The focus of the research was on the actual processes of aggregate production in the Sri Lankan construction industry, and this enabled the collection of relevant data to achieve the research objectives. Accordingly, research adopts a mixed approach. Semi-structured expert interviews and a questionnaire survey were adopted as the research's data collection methods to ascertain and validate the identified production processes, cost and benefit centers, and all associated information through the literature review and gather further information. Accordingly, there are two phases of data collection: Phase I (expert interviews) and Phase II (questionnaire survey). Existing literature examines the production processes of recycled aggregates and how they vary from the natural aggregates, however, the objective of this study is to apply the framework to a particular functional area in the selection of materials for a particular project. Consequently, one of the primary purposes of expert interviews was to determine the production processes and validate the identified cost and benefit centers of each. In addition, another purpose was to facilitate the development of the framework in the subsequent phase. Through expert interviews, all the literature findings were validated, and the main cost and benefit centers were pinpointed accordingly.

As indicated in Table 1, interviews were conducted with eight (8) industry experts who identified as subject matter experts were determined via purposive sampling. An expert from a recycling plant was interviewed and one (1) separate interview was conducted with a quarry operator. Also, six (6) semi-structured interviews were conducted to gather experts' perspectives, views, and ideas on the study and validate the data identified through the literature review. Those focal experts were selected to cover a spectrum of construction professionals with knowledge of sustainability, environmental professionals, experts with extensive involvement in concrete recycling plants or operating quarries, and academics with a research interest in sustainability. In addition to that, the questionnaire was circulated among construction professionals, considering the relevance of their expertise to the study. For that, researchers have aimed for a diverse pool of participants through non-random sampling to capture varied perspectives and enhance the richness of data. Out of 44 respondents, 34% were engineers, 27% were quantity surveyors, 14% were project managers, 9% were architects, and 19% were contractors. The questionnaire was created so respondents could rate their responses according to their individual opinions.

Table 1- Profile of Phase 1 (Expert interviewees)

Code	Designation	Experience (No. Years)
P1:01	Site supervisor-Recycling plant	14
P1:02	Quarry operator	33
P1:03	Structural Engineer	21
P1:04	Professor in Civil Engineering	28
P1:05	Chartered Quantity Surveyor	15
P1:06	Environmental Engineer	11
P1:07	Senior Lecturer in Civil Eng.	32
P1:08	Civil Engineer	16

For data analysis, content analysis with manual coding was used due to the requirement to limit the volume of data collected and to facilitate classifications by enhancing the contextual meaning. It is imperative to highlight the significance of the identified cost and benefit centers of the framework. For that, the Relative Importance Index (RII) method was used to rank the identified cost and benefit centers. Finally, a framework is made to decide on the appropriateness of RCA in place of NA in a construction project in Sri Lanka.

4. Expert Interview, Questionnaire Survey, Data Analysis and Discussion

Following the literature review expert interviews, and questionnaire survey, the data analysis focuses on the evaluation of research findings. The phase I interviews were analyzed to validate the literature and verify the cost and benefit centers of the production of both natural and recycled aggregates and to facilitate the subsequent framework development. Afterward, the intermediate framework was developed based on findings from the questionnaire survey, literature, and respondent perceptions from Phase I.

4.1 Sources of generating discarded concrete in the Sri Lankan construction industry

Demolition, renovation, and maintenance of old structures were identified in the literature as key sources of enormous volumes of discarded concrete. To validate these findings, this question was included in the survey, and according to the responses of the participants, the primary source of waste concrete is the demolition of old structures. The renovation and maintenance activities also produce a large amount of discarded concrete. Also, concrete waste at construction, acquisitions for development activities, damaged structures due to exceptional events, structural failures of the constructions, pre-cast industry, and overproduction in ready mix plants are identified as potential sources. However, each of these sources directly and indirectly contributes to the generation of a large amount of discarded concrete.

4.2 Production Processes of RCA and NA in Sri Lanka

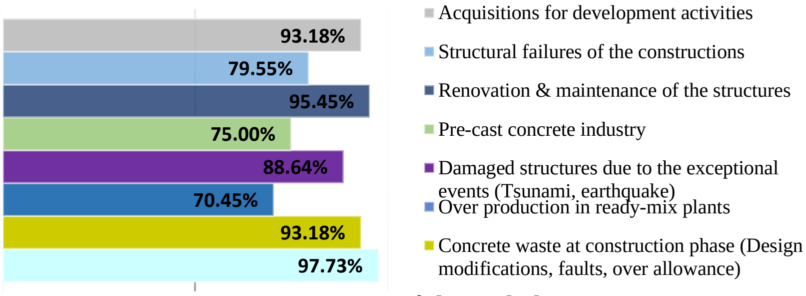

Figure 1:Sources of discarded concrete generation.

According to the site supervisor of the recycling plant and the quarry operators, the process of converting discarded concrete into coarse aggregate is identical to the process of aggregate crushing. The literature findings on the process of natural aggregate production were confirmed through the interviews and identified several cost and benefit centers. Accordingly, the process flow of natural aggregate production and recycled concrete aggregates can be depicted as follows.

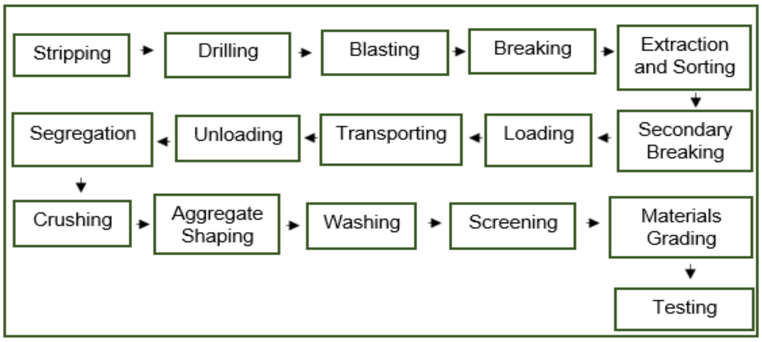

Figure 2:Process flow of RCA.

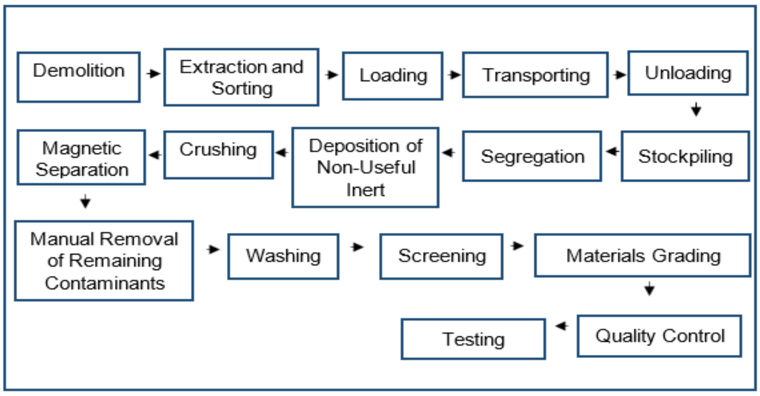

Figure 3: Process flow of NA.

4.3 Cost and benefit centers for aggregates production

Relevant cost and benefit centers of the concrete recycling process and natural aggregate production process for a cost-benefit analysis that were identified through the literature review and interviews with quarry operators and recycling plant supervisors are added to the interview guideline and all the interviewees agreed on the identified cost centers and added several centers as well.

Cost centers

In addition to the main work items, water pollution, and embodied energy are the mainly focused environmental costs. Here P1:05 emphasized that the generation of wastewater and the water consumption of the particles must be considered. Moreover, quarry operations are directly impacted by groundwater contamination. Also, gas emissions and all the energy consumption for the process are categorized as embodied energy. Intangible costs like worker's health risk cost and cost of negative externality (noise pollution, air pollution) must be considered. Additionally, according to P1:02 and P1:03, the costs for mandatory legislation such as local taxes, permit costs, and insurance costs should be reviewed separately for the two alternatives. This is because, for quarry operations, a significant amount of permit costs and taxes have to be paid by the local government. After all, it negatively impacts the environment more than RCA production.

Benefit centers

The main benefit centers of recycled concrete aggregates are pinpointed as the reduction of fresh extraction of natural aggregate, conserve landfill space, revenue from selling scraps (Eg: reinforcement bars), reduction of transportation, waste reduction, elimination of hazardous quarry operations, environmental benefits, and intangible benefits. Furthermore, according to P1:04's opinion recycled aggregates are lighter weight than virgin quarry products. Thus, it provides superior constructability and compaction. Intangible benefits that must be considered in the cost-benefit analysis are affirmed as; improved public image and environmental concern, and reduced liabilities including responsibility for environmental issues. Based on the interviews, all experts emphasized that the structural performance of natural aggregates is very high, and it is a highly significant factor. Furthermore, P1:02, P1:05, and P1:07 suggested that the use of NA is beneficial because the cost of demolition and treatment is significantly higher. Consequently, these two (02) benefits centers were also added to the analysis.

4.4 Evaluation of the significance of the cost and benefit centers

The questionnaire enabled the respondents to rank cost and benefit centers based on their significance thereby determining their relative importance. After calculating the RII value, the mean of the RII is taken and then the variance is derived by subtracting the mean value from the RII value of the respective centers. Afterward, each cost and benefit centers were ranked accordingly. If the variance is positive, the cost-benefit center is critical and thereby prioritized. If the variance is negative, those cost and benefit centers were considered not significant to be included in the framework.

Accordingly, the costs of manual removal of remaining contaminants, labor' health risk cost, cost of negative externality, permitting costs, local tax, and insurance costs were found to be not very significant for RCA. The benefits are revenue from selling scrap (Eg: reinforcement bars), reduction of transportation, reduced greenhouse gas emissions, conservation of energy and natural resources, less chance of soil and groundwater contamination, and reduced liabilities including responsibility for environmental issues are not significant for the cost-benefit analysis. In addition, for NA, the costs of stripping washing, testing, and water pollution cost are not very significant for the cost-benefit analysis. Also, the benefit of no demolition fees is not very significant for the cost-benefit analysis.

4.5 Assessment of the intangible costs and benefits of the framework

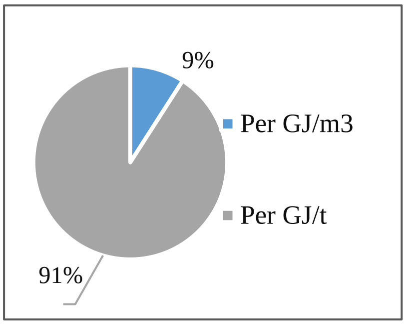

Figure 4: Assessment basis of the embodied energy.

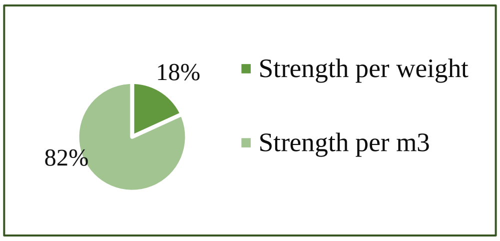

Figure 5: Assessment basis of structural performance.

Structural performance

According to the expert interviews and the literature, structural performance is the key benefit of utilizing NA. Therefore, the structural performance has to be measured and according to the experts, the assessment basis of the structural performance is per m3. And shadow pricing technique to be assigned to convert intangible benefits to a tangible parameter.

Embodied energy

The framework considers energy use and CO2 emissions under embodied energy. According to the results of the questionnaire survey, the assessment basis for embodied energy is in terms of GJ/t. (Figure 04)

Framework to decide on the appropriateness of RCA

Table No. 2 shows the framework, which is proposed by the study to utilize RCA consumers when decision-making on whether to use RCA or not at a given instance.

Table 2: Framework for the appropriateness of RCA

Costs of RCA	X	Y	Z	Benefits of RCA	P	Q	R
Demolition Extraction and sorting Transporting Loading & unloading Stockpiling Segregation Deposition of non-useful inert Crushing				Reduction of fresh extraction of NA Conserve landfill space Waste reduction **Elimination of hazardous quarry** **operations like;** High noise levels Excessive vibrations Health risk- dusty atmosphere,			

Magnetic Separation Washing Screening Materials grading Quality control cost Cost of testing Dealing with dust **Environmental cost** Water pollution cost Embodied energy				heavy machinery (hand-held tools & etc.) and the use of explosives Air pollution and noise pollution Degradation of land and vegetation Land subsidence and landslides Depletion of groundwater and forests Loss of biodiversity **Environmental benefits** Resource conservation Reduced space wastage in landfills Diversion of waste from landfill As a solution for over-over-exploitation of quarries Reducing embodied energy and carbon footprint from mining **Intangible benefits** Improved public image and environmental concern			
∑PV of all the Associated Costs of RCA (A)				**∑PV of all the Expected Benefits of RCA (B)**			
Costs of NA	**X**	**Y**	**Z**	**Benefits of NA**	**P**	**Q**	**R**
Drilling Blasting Breaking Extraction and sorting Secondary breaking Transporting Loading & unloading Segregation Crushing Aggregate shaping Screening Materials grading Dealing with dust **Environmental cost** Embodied Energy **Intangible costs** Laborers' health risk cost Cost of negative externality, - (Noise, air pollution) **Mandatory legislations** Permitting costs Local Tax Insurance				Structural performance			
∑PV of all the Associated Costs of NA (C)				**∑PV of all the Expected Benefits of NA (D)**			

Here,

Net Benefit of RCA (E) =∑PV of all the Expected Benefits of the Associated Costs of RCA (A)	(2)	RCA (B) -∑PV of all
Net Benefit of NA (F) =∑PV of all the Expected Benefits of NA Associated Costs of NA (C)	(3)	(D) -∑PV of all the
Net benefit of RCA over NA (G) = Net Benefit of RCA (E) - Net	(4)	Benefit of NA (F)

X = Initial costs
Y = Operational / Time related costs
Z = PV of costs

P = Initial Benefits
Q = Operational / Long term Benefits
R = PV of benefits

$$\boldsymbol{Net\ Benefit} = \sum \textbf{PV of all the Expected Benefits} - \sum \textbf{PV of all the Associated Costs} \qquad (1)$$

4.6 Decision on the appropriateness of recycled concrete aggregates

To evaluate the appropriateness of recycled concrete aggregates, this proposed framework can be effectively utilized and for that, all the cost and benefit centers of recycled concrete aggregates and natural aggregates that have to be considered are outlined in detail. Present values of all associated costs and the present value of all expected benefits should be taken. To decide on the appropriateness of recycled concrete aggregates, below below-mentioned details should be considered.

IF G>= 0, appropriate to use RCA
IF G< 0, appropriate to use NA

4.7 Applications of recycled concrete aggregates

Conclusively, several applications of RCA have been identified within the context of the construction industry in Sri Lanka. Various authors have evaluated the application of recycled aggregates, which is dependent on the quality of the discarded concrete, and numerous treatment procedures can improve the aggregates' quality as well. Interviewees' perception was that RCA can be applicable for road construction projects, the production of alternative building materials like blocks, as a filling material, and for mass concrete (below G25). In the literature also, researchers have proven that recycled concrete aggregates can be used for structural concrete as well. Among these, according to the questionnaire, all the professionals agreed that RCA can be effectively utilized as a filling material. According to the interviewees and 41 respondents, RCA cannot be utilized for the mass concrete (above G25). Furthermore, according to some of them, there was a divergence of opinions concerning the application of retaining walls and mass concrete with compressive strengths below G25 as well. Therefore, as a filling material, as sub-base materials for road construction projects, and to produce alternative building materials like blocks the RCA can be utilized effectively. To decide the appropriateness, the above-described framework can be used as well.

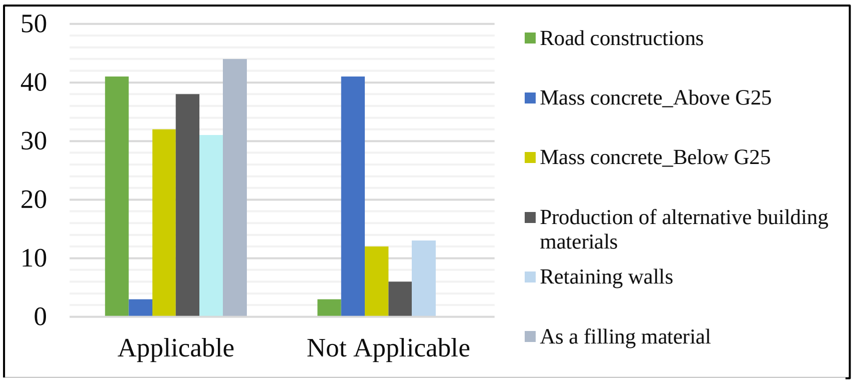

Figure 6: Applications of RCA.

5. Conclusion and Recommendations

The main aim of this study is to develop a framework to decide the suitability of the recycled aggregates and to achieve the objective, the foundation was laid via the literature review and continued across data collection and analysis. According to the researchers and experts, a variety of cost and benefit centers were identified, therefore through a questionnaire survey the significance of those identified cost and benefit centers was checked and 44 industry professionals responded to the questionnaire. The cost and benefit centers were ranked according to the RII method. Afterward, the cost and benefit centers that had positive variance were included in the framework. To determine the appropriateness, present values of all the associated costs and expected benefits should be assessed for each alternative. If the net benefit is larger than or equal to zero, it is appropriate to use RCA and if not, better to use NA. Thus, this research proposed a framework for determining the appropriateness of utilizing recycled concrete aggregate. The framework and methodology provided in this research are essential for evaluating and selecting the preferred aggregate type to be utilized in projects. This will enable the quantity Surveyors, architects, engineers, and contractors, to improve their environmental response while not compromising on the business objectives in the construction industry. The primary recommendations concentrate on raising awareness and effectively implementing the framework in construction projects. For the framework to function effectively, organizations must combine the required expertise and knowledge and implement the model practically to test and generate outcomes. If the development of the RCA concept results in the addition of insurance, licensing costs, and local tax to concrete recycling, those should also be addressed in the framework. Moreover, this framework can be applied to the applications that are confirmed by experts, and the appropriateness of using recycled concrete can be determined. And to optimize the use of recycled concrete, the research findings recommend the government establish new policies to encourage the recycling of construction and demolition debris. The high cost of landfills and the lack of available land make it impossible to properly dispose of all materials produced by demolition. Therefore, a solution to this problem is to establish more construction waste recycling centers at strategic locations across Sri Lanka.

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IMPACT ON LARGE-SCALE BUILDERS OF THE CONSTRUCTION INDUSTRY IN SRI LANKA IN THE FACE OF THE CURRENT ECONOMIC CRISIS

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Abstract: The construction industry plays a significant role in the country's national economy in terms of generating wealth and improving living standards. This strong correlation and the resulting contribution to the GDP warrant the need to ensure that all construction projects are executed as efficiently as possible. Since 2022, Sri Lanka has been experiencing its worst economic crisis in decades. This has had a detrimental effect on many economic sectors, including the construction industry. To take remedial actions, it is necessary to conduct an in-depth analysis of how the industry has been impacted negatively. The scope of this study focuses on large-scale Sri Lankan builders, and it aims to identify the payment problems as well as other constraints faced by them due to the economic crisis. The objectives set to achieve the stated aim were to explore the impacts of the current economic crisis in Sri Lanka with special emphasis on the construction industry, determine the impact of the economic crisis on large-scale builders, and identify existing strategies used by large-scale builders to avert negative impacts and provide recommendations for better performance. Preliminary interviews were conducted with construction industry experts (n=5) and their responses were used as a guideline when preparing the questionnaire survey to identify the main issues faced by large-scale builders within the industry. The responses (n=42) concluded that the construction industry in Sri Lanka has been greatly affected by the economic crisis and that the uncontrolled increase in construction material prices had served to impact and worsen the cash-flow issues faced by large-scale builders. The study recommends that rather than resorting to local projects, large-scale builders would better opt to undertake international projects during this time.

Keywords: Economic Crisis; Large-scale builders; Construction Industry; Improvement Strategies

1. Introduction

The construction sector is crucial to the socio-economic development of any nation. The potential for employment generation, economic support, public regulation, as well as income distribution can all be seen as aspects of the construction industry's role in the economy (Pheng and Hou, 2019). However, the recent economic crisis in Sri Lanka has had a substantial impact on the construction industry, limiting the nation's capacity to fully realize the benefits of investing in the building sector (George, George, and Baskar, 2022). Since 2019 – when the crisis' impacts first became evident – until now, the construction industry has seen a steady decline, leading to a stagnated state by the first quarter of 2023. Over this time, the construction industry suffered from thousands of job losses and a sharp downturn in building projects as a result of rising raw material prices, fuel scarcity, and power outages (Wijeratne N., 2022). The decrease in construction activity within Sri Lanka was especially alarming given the pivotal role that it plays in enabling and uplifting the performance of multiple other economic sectors (George, George, and Baskar, 2022). Therefore, thoughtful, and strategic steps must be taken to address the existing problems and promote the revival of the construction industry in Sri Lanka.

The concepts of delay, disruption, and cost overrun are especially relevant within the construction industry amidst an economic crisis (Gammanage and Gunarathna, 2022). With the weakening of the Sri Lankan rupee against the US dollar, the costs of all building materials have risen, posing a significant strain on the construction industry's stakeholders (De Silva, 2023). Large-scale Contractors have been particularly hard hit by the economic downturn and have faced several specific challenges as the crisis hampered their capacity to carry out existing projects, as well as to start new ones. As evidenced by Fadhil and Burhan (2021), economic crises lead to a depletion in construction projects, causing mass unemployment, particularly within the contractor businesses. Studies have been conducted with small and medium-sized contractor groups in focus, to discover the financial constraints affecting their workforce (Sriyani, 2022; Edmund, Yang, and Eric, 2018). However, there is a gap in the knowledge of what issues uniquely affect large-scale contractors in Sri Lanka and the potential solutions to these problems. Therefore, there is a necessity to explore this situation thoroughly and recommend urgent solutions to avert the worst effects of the economic crisis. Therefore, this research aims to identify the factors that cause payment problems and constraints for large-scale builders in Sri Lanka due to the current economic crisis. In the context of this study, "large-scale builders" refers to construction organizations with a C1 or higher CIDA grading with a minimum annual turnover of Rs. 50 million. To achieve the aim of this study, the following objectives have been set for this study: Exploring the prevailing economic crisis in Sri Lanka and its impact on the overall economy of the country with special emphasis on the construction industry; Exploring the impact on construction contractors with special focus on the implications on large scale contractors; Identifying existing strategies used by large scale contractors to avert the negative impact due to this crisis and proposing recommendations to improve their performance.

2. Literature Review

2.1 Impact of the economic crisis of Sri Lanka on the construction industry

Over the course of the past twenty years, the Sri Lankan construction industry has experienced numerous fluctuations ranging from dramatic rises to severe recessions. Following the end of a decades-long civil war in 2009, massive investment inflows caused the construction sector to experience an extraordinary boom, greatly increasing the country's GDP (Bhowmick, 2022). However, with the unanticipated spread of the COVID-19 pandemic in 2019, the construction industry once again faced a massive blow which then paved the way for its gradual downfall (De Silva, 2023).

The poor performance of construction projects is a significant issue in Sri Lanka's construction industry that requires immediate action, especially in the wake of the economic crisis (Ariyarathna *et al.*, 2020). This strategic significance stems from the necessity of structures and infrastructure to enable the development and expansion of multiple other economic sectors (Pheng and Hou, 2019). In other words, the construction services industry is a crucial sector that can spur the growth of other industries. Sri Lanka's construction sector is facing debilitating cash flow constraints that have become the underlying cause of several problems for local contractors, crippling their ability to bid on large-scale state projects and halting existing projects (Fernando, 2023; Sivarajah, 2021).

2.2 Impact of the economic crisis on large-scale construction contractors of Sri Lanka

De Silva, Wijekoon and Kalugala (2023) point out that construction sector crises are unavoidable given the very nature of the industry, as well as the intensive human involvement within it. Due to the current economic crisis, contractor organizations have faced numerous challenges such as not receiving progress payments on time, increased costs for primary building supplies, inability to pay employees, limitations on the import of goods, and resultant financial issues for both employer and contractor (Fraser and Silva, 2019).

The government's lack of foreign reserves to import gasoline resulted in severe fuel and energy shortages, lengthy lines at gas stations, and a fuel black market, placing further strain on citizens (Shehan *et al.*, 2022). In the following months, harsh measures such as suspension of essential transport services, closing schools and workplaces, implementing curfews and work-from-home policies, and temporarily banning fuel sales for non-essential vehicles had to be taken to conserve the remaining fuel within the country (Sooriyaarachchi and Jayawardena, 2023). The fuel shortage saw a steep increase in transportation costs, which in turn resulted in massive price hikes for raw materials such as cement, sand, and metal. Kabirifar and Mojtahedi (2019) observed that these issues created unnecessary cost overruns in projects, ultimately causing financial losses for large-scale builders.

Obtaining bank loans to govern cash flow was a viable option for most large-scale contractors before the economic crisis. However, the economic crisis caused banks to boost interest rates on loans, forcing contractors to re-evaluate and reassess bank borrowings (Fernando, 2023). The interest rate is a market indicator, and a key driver of a company's actions. Therefore, regardless of an organization's operation, interest rate risk (IRR) will have a direct influence on its decisions on investments, dividend payments, interest-bearing investments, opportunity costs, and financing. Therefore, organizations within the construction industry are especially sensitive to IRR (Bickerton and Gruneberg, 2013).

As observed by Inderst and Stewart (2014), banks are a popular option for debt financing within the construction industry, because they facilitate loans and borrowings. Past research has identified six main factors that directly impact interest rates: supply and demand for credit; competition in the loanable market; and economic factors such as inflation, expectations of investors, the monetary policy of the government, and uncertainties (Manamgoda, Perera, and Perera, 2018).

The construction industry is significant, not just in terms of its end product, but also for the sheer number of people it employs. Unskilled laborers, semi-skilled laborers, skilled laborers, and construction professionals are among the many types of workers this industry employs. The Department of Census and Statistics (2022), states that approximately 1.5 million individuals, representing around 7.6% of the total workforce of Sri Lanka, have been employed by the construction industry.

2.3 Strategies to overcome issues faced by large-scale builders due to the economic crisis.

Several strategies have been proposed through past literature that aim toward the upliftment of construction activity and construction organizations in times of crisis. Öcal, Oral, and Erdiş (2006) investigated crisis management within the Turkish economy, with special emphasis on the strategies implemented by construction organizations to overcome the adverse effects. It was concluded that while only a small number of companies had utilized a systematic crisis-management strategy, those that did, however, emerged on a better footing than the rest when the crisis was being resolved. Further, (Öcal, Oral, and Erdiş, 2006) found that the more successful organizations had utilized contemporary decision-making methods to strategically reposition themselves amidst the crisis. An investigation into risk management in construction organizations that was conducted in the context of the Lebanese economic crisis revealed that the proper implementation of risk management strategies will reduce project losses while increasing the possibility of project success (Shibani *et al.*, 2022). Babu and Sudhakar (2016) recommend that in the face of economic crises, construction companies should focus on specialized projects while improving consistency in project planning. Furthermore, strategic analyses of the internal and external environment, macroeconomic data and foreign exchange, interest rates, unemployment rates, and emerging legal and political regulations must be done proactively. To avert the adverse effects of crises, proactive measures must be taken to ensure restricted expenditures and centralized management (Babu and Sudhakar, 2016). Globalization has ensured that the construction industry is no longer a local market and in response to these rapid changes, most developed countries have opted to adopt strategies of internationalization, allowing them to benefit from the global market (Horta *et al.*, 2012).

3. Methodology

This study aims to identify the payment problems and other constraints faced by large-scale contractors due to the 2019-2023 economic crisis in Sri Lanka. To achieve the stated aim, a mixed-method research approach was taken consisting of data analysis in both qualitative as well as quantitative methods. Data collection was done first through preliminary interviews, and then through a questionnaire survey. A purposive sampling technique was used to focus only on professionals from the construction industry. Primarily, preliminary interviews were conducted where the focused views of qualified and experienced construction professionals (n=5) were collected and analyzed. The findings of the preliminary interview were used to prepare the questionnaire survey to identify the issues that have affected the construction industry overall, as well as the large-scale builders specifically. The survey consisted of multiple choice, Likert scale, as well as open-ended questions (n=11). Likert scales ranging from 1-4 were used to measure the impact on the construction industry and Large-scale builders. The options ranged from 'No impact', 'Low impact', 'Slight impact', and 'High impact'. Further, strategies that are practiced by Large-scale builders were found through ranking on Likert scales ranging from 1-5, which contained the options 'Not practiced', 'Less practiced', 'Moderate', 'Commonly practiced', and 'Highly practiced'. The questionnaire was distributed among construction professionals (n=42) consisting of quantity surveyors, engineers, project managers, architects, and CEOs of construction companies with over 10 years of experience. The gathered data was analyzed using both statistical and thematic analysis techniques. The data collected through the Likert scale was analyzed and ranked using the weighted mean approach.

Eq 1: Formula to calculate the weighted mean

$$W = \frac{\sum_{i}^{n}=1^{\omega_i X_i}}{\sum_{i}^{n}=1^{\omega_i}}$$

W = Weighted mean
ω = Frequency of responses
n = Number of terms to be averaged
ω_i = Weights applied to x values
X_i = Data values to be averaged

4. Analysis and Discussion

The purpose of this study is to provide a better understanding on the impact of the current economic crisis on the construction industry and deduce the specific burdens and constraints caused by it towards large-scale contractors. The data for analysis was gathered in two main ways: preliminary interviews and questionnaire survey. Preliminary interviews were conducted to narrow down the existing body of knowledge gathered through the literature survey and obtain focused factors to be evaluated through the questionnaire survey. The primary data collected through the questionnaire survey established that each respondent had over 5 years of experience in the construction field and had been associated with large-scale contractors at least once throughout their career. This allowed the respondents to provide more accurate answers for later questions which were in the context of large-scale builders of Sri Lanka. Initially, respondents were inquired how the economic crisis has affected their construction organization and 62% of respondents (n=26) answered that their organization has been severely impacted.

The first objective of the study was to explore the impacts of the current economic crisis in Sri Lanka with special emphasis on the construction industry. Thereby, through analyzing the first round of gathered data, the specific impacts of the economic crisis on the construction industry were deduced. Preliminary interviews revealed 7 key impactful factors to be ranked in terms of the impact that they had on the construction industry. These factors were tested in the questionnaire survey using a Likert scale and subsequently ranked using the weighted mean method. Table 1 depicts the rankings obtained through the weighted mean method.

Table 1: Ranking of factors that impacted the construction industry due to the economic crisis

Factors	Weighted mean	Rank
Inability to commence projects as planned due to funding issues	3.690	1
Increase in construction material prices	3.667	2
Difficulty in setting project budgets due to uncontrolled increases in material prices	3.643	3
Inability to set a fixed rate while estimating for new projects due to increases in price resources	3.619	4
Fuel shortage	3.595	5
Inability to proceed with specialized projects due to funding issues	3.524	6
Construction worker migration from the country	2.976	7

The main impact of the economic crisis on the construction industry is the disruption of funding for construction activities (WM = 3.690). Interviewees were also of the general opinion that the country's main issue in the context of the economic crisis was that the number of projects implemented could not be sustained and carried out successfully due to the dire financial situation. The soaring and uncontrolled cost of construction material prices ranks second in terms of the impact (WM = 3.667). The third and fourth ranking issues—the difficulty in establishing project budgets (WM = 3.643) and the inability to establish fixed rates when estimating (WM = 3.619)—are also directly impacted by the element of increased material prices. It should come as no surprise given the importance of cost planning in construction project management, that the chance for project sustainability is almost entirely lost in the face of an unforeseen circumstance like the economic crisis. Fuel shortage (WM = 3.595), inability to carry out specialized projects (WM = 3.524), and construction worker migration (WM = 2.976) are also factors that were recognized as having an impact on the construction industry. Through analysis, it can be concluded that these factors have a lesser impact comparatively, but ultimately also have the potential to disrupt construction activities if strategic measures are not taken to address them.
The second and main objective of the study is to determine the impact of the economic crisis on large-scale builders. Therefore, the preliminary interviews were primarily focused on deducing factors that specifically impact large-scale builders, and 8 such factors were compiled to be included in the questionnaire survey. The factors were then tested using a Likert scale and ranked using the weighted mean method similar to the previous set of factors. Table 2 depicts the rankings obtained through the weighted mean method.

Table 2: Ranking of factors that impacted large-scale builders due to the economic crisis

Factors	Weighted Mean	Rank
Material price increases	3.690	1
Issues in maintaining cash flow	3.643	2
Time overruns	3.643	2
Non-payment for government projects (Local funded projects)	3.619	4
Non-payment or delayed payment	3.571	5
Restriction of import good	3.548	6
Uncertainty of the job opportunities in the industry	3.429	7
Sell other assets of the business to honor liabilities	3.214	8

As evidenced by the rankings, the most significantly impactful factor is the increase in material prices (WM = 3.690). With the global economic crisis triggering disruptions in the construction material supply chain, and the local political and economic crisis only serving to worsen the issue, large-scale contractors are faced with both a shortage of construction materials as well as escalating costs (De Silva, 2023). Large-scale contractors are also facing the severe impact of issues in maintaining cash flow (WM = 3.643). In a recent interview with *The Daily Morning Business*, Nawaloka Construction CEO Mr. Kalana Alwis expressed concerns over the dire situation that most large-scale contractors are facing due to cash flow issues. According to him, the lack of cash flow has been the root cause of conflict between banks and large-scale contractors, causing banks to pursue litigation and asset acquisition (Fernando, 2023). Time overruns (WM = 3.643) are another significant issue for large-scale builders. This factor raises concern over interminable delays in existing projects, which will only serve to cause cost overruns as well. Other impactful factors (consecutively ranked) include Non-payment for government projects, Non-payment / delayed payment in general, Restriction of import goods, dwindling number of job opportunities, and having to compromise existing assets.

The final part of the preliminary interviews consisted of questions about the remedial actions that interviewees have already seen taken by large-scale builders to mitigate the negative impacts of the economic crisis, as well as the strategies that they would recommend for large-scale builders. The answers given by interviewees were compared with literature findings and 8 strategies were formulated to be included in the questionnaire survey. Respondents were asked to rank the strategies on a Likert scale based on how commonly they were being practiced in their respective organizations. Table 3 illustrates the rankings obtained through the weighted mean method.

Table 3: Ranking of strategies taken by large-scale builders due to the impact of economic crisis

Factors	Weighted Mean	Rank
Cutting down unnecessary expenditure, minimize additional allowances	4.190	1
Doing projects for private clients (Avoid government-funded projects)	4.024	2
Reduce Workforce	3.952	3
Getting the raw materials required for future projects in advance	3.857	4
Participate in projects funded by World Bank ADB (Reliable donor agencies only)	3.857	4
Prioritize projects in tendering (Tenders which associated with CIDA price fluctuation clauses)	3.786	6
Prioritize projects in tendering (Where there will not be perceived funding issues)	3.762	7
Stop the progress of construction activities	3.429	8

The rankings indicate that the most common strategy used by large-scale builders is cost optimization by cutting down unnecessary expenses and minimizing allowances (WM = 4.190). Other common strategies include prioritizing private projects (WM = 4.024), Reducing workforce (WM = 3.952), Acquiring raw materials in advance (WM = 3.857), and Prioritizing projects funded by World Bank, ADB, and other reliable donor agencies (WM = 3.857). Organizations have also adopted the strategies of project prioritization at different levels of bidding based on more careful attention to contract administration (WM = 3.786, WM = 3.762). Project suspension or termination (WM = 3.429) is also an option for most large-scale builders, as a strategy to preserve cash flow and resources for more promising projects. However, given its low ranking, it can be deduced that it is a last-resort strategy for most large-scale builders.

5. Discussion

The economic crisis had a significant negative impact on existing large-scale builders, as well as new builders who are set to enter the market. Expert opinions were sought to validate this fact and the interviewees commented on the hesitation of new contractors to enter into the construction sector, as well as the causes for the departure of existing contractors. This attitude likely stems from the reality that most new contractors as well as existing contractors have been unable to find new projects due to the economic crisis. With the Government of Sri Lanka (GoSL) focused on other economic avenues for revenue generation, government-funded project opportunities have dwindled. Thereby, new builders hesitate to partake in bidding for construction projects, while existing large-scale builders seek better opportunities by subcontracting for foreign projects.

However, based on the findings of this study, there is a strategic advantage for new builders during this time to enter the market easily. With existing large-scale builders with higher work capacity and more resources focusing on international projects, opportunities are created within the industry for new builders to undertake local projects. The gap in the market created because of the migration of experienced workers could also create more employment opportunities for new workers. Thereby, it is inadvisable for old, as well as new contractors to remain stagnant during this time. The most prudent course of action for large-scale builders is to strategically change their focus from local projects to international projects, as well as to collaborate with foreign investors. This change would create opportunities, not only for large-scale builders but also for new builders within the construction industry.

This study recommends the following strategies for large-scale builders, to overcome the constraints caused due to the economic crisis:

1) GOSL should conduct awareness programs for foreign investors to invest their money in the construction industry
2) Contractors should be given opportunities to directly import raw materials using their foreign currency
3) Prioritize projects funded by ADB and WB (reliable donor Agencies)
4) Completion of ongoing projects at the earliest possible,
5) GOSL should provide fuel to proceed with ongoing construction projects,
6) Minimize company overheads,
7) The Government of Sri Lanka (GOSL) should release pending payments for contractors as soon as possible
8) Engage in foreign construction projects (in countries like Maldives).

6. Conclusion

This study was conducted to identify payment problems as well as other constraints faced by large-scale builders due to the economic crisis. The objectives set to achieve this aim were: to explore the impacts of the current economic crisis in Sri Lanka with special emphasis on the construction industry, determine the impact of the economic crisis on large-scale builders, and identify existing strategies used by large-scale builders to avert negative impacts and provide recommendations for better performance. Both preliminary interviews with experts as well as a questionnaire survey with a considerable sample size were used to gather data for this study. Through a detailed literature review, as well as a mixed-method approach to data analysis, it was made evident that the economic crisis had a significant negative impact on the construction industry. Through the first objective, this impact was examined thoroughly, and it was concluded that the most notable struggles were due to the inability to commence projects due to financial constraints, increase in material prices, and difficulty in budgeting and cost estimation. Large-scale builders face several issues. The most critical issues were found to be due to increases in material prices, cash-flow constraints, and time overruns. Based on the literature findings, data analysis rankings, and expert opinions, this study has recommended 8 key strategies for large-scale builders to follow. This study concludes that in following these strategies, large-scale builders shall be better equipped to handle the difficulties resulting from the economic crisis while planning for prospective future challenges and contingencies.

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ASSESSMENT OF THERMAL COMFORT LEVELS IN TYPICAL SCHOOL BUILDINGS IN THE SOUTHEASTERN REGION OF SRI LANKA

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Abstract: Thermal comfort inside the learning environment has a substantial impact on students' performance and mental acuity. Providing a thermally comfortable condition inside the classrooms is a challenging task, in regions where the climate is hot and humid. This study focused on examining the thermal comfort levels in naturally ventilated typical classrooms in Sri Lanka. A study was conducted to assess thermal comfort levels in two different school buildings in the South-Eastern region of Sri Lanka. The assessments included measurements of climatic parameters and a questionnaire-based survey with students to assess thermal comfort levels using the ASHRAE thermal sensation scale in the classrooms. The mean indoor temperature and relative humidity measured during the study period were 30.5 ºC and 75.8% respectively. The survey revealed that 68.5% of students voted within the comfort band (-1 to +1) according to the ASHRAE thermal sensation scale. The thermal preference of students showed a preference towards a cooler sensation and an increased air movement. The data analysis indicated that for these naturally ventilated school buildings, a neutral temperature of 28.5 °C and a comfort range of 25.9 °C to 31.0 °C, with 80% acceptability, are applicable. Griffith's method predicted a mean comfort temperature of 28.9°C.

Keywords: Adaptive strategies; Naturally ventilated classrooms; School buildings; Thermal comfort

1. Introduction

Thermal comfort refers to the state of mind that reflects satisfaction with the current thermal environment. The psychological, physiological, and behavioral factors also influence the thermal comfort perceptions of people. In addition, various other parameters including air temperature, airspeed, relative humidity, radiant temperature, metabolic rate, and clothing insulation also affect thermal comfort levels (ANSI/ASHRAE Standard 55-2010, 2010). Past studies revealed that thermal comfort in classrooms has a significant effect on students' learning abilities (Heracleous & Michael, 2020), such as reading comprehension, reading speed, and passing rate in examinations. Therefore, maintaining the thermally comfort classrooms is one of the key issues in managing the educational learning environment, therefore proper care should be taken in the planning and designing classroom environment. Several research studies were conducted worldwide to investigate the thermal comfort conditions inside the classrooms.

The recent research conducted on these aspects has been based on the adaptive comfort theory strategy, where they estimate the occupants' thermal comfort conditions considering both the measurement of climatic variables and the evaluation of subjects' votes from field surveys (Jindal, 2018). The adaptive principle states that, when the occupant feels thermal discomfort, the occupant will react consciously or unconsciously in such ways to bring back the surrounding environment to thermally comfortable levels (Corgnati et al., 2007). Results obtained for the acceptable temperature limits from the past thermal comfort studies deduce that the students perform several adaptive actions to keep the surroundings thermally comfortable (Mishra & Ramgopal, 2015). However, these adaptive actions performed by students to keep their surrounding environment thermally comfortable have led to an increment in energy consumption, and that in turn affects the sustainability of the building set-up (Katafygiotou & Serghides, 2014). Although various studies related to thermal comfort levels in school buildings have been reported in the literature, thermal comfort characteristics in school buildings in tropical countries, especially in countries like Sri Lanka, where hot and humid climate prevails throughout the year are not well explored.

In Sri Lanka, nearly 20% of the total population are school students, they spend approximately one-fourth of their day inside school buildings (Statistics Branch of Ministry of Education of Sri Lanka, 2020). Mostly, developed countries use cooling devices such as air- air-conditioners (AC) to maintain thermal comfort within a suitable range in classrooms. However, those measures increase the overall energy consumption which in turn increases the cost of operation and maintenance of the school buildings, where they are cost-effective, particularly in developing countries like Sri Lanka. Therefore, one of the options is to use naturally ventilated school buildings in tropical climate regions, which is mostly the case in developing countries, such as Sri Lanka. This approach facilitates maintaining the classrooms thermally comfortable to a certain extent, however, the level of thermal comfort achieved should be verified.

The school buildings in Sri Lanka follow certain typologies, regardless of the location they are constructed, as the building configuration is generally designed and approved by the building works division of the Ministry of Education. Therefore, the thermal comfort levels in school buildings should be assessed systematically and necessary modifications should be made to adapt to the change in climatic conditions. To address this research gap, a study was conducted to evaluate the thermal comfort conditions of naturally ventilated classrooms in Sri Lanka. Two school buildings on the South-Eastern coast of Sri Lanka were specifically selected for the study. The key objectives of the study are:

- To evaluate the thermal comfort conditions of students in naturally ventilated classrooms;
- To determine the neutral temperature and comfort temperature range felt suitable by the student population, and;

- To identify the students’ adaptive behavior during classes in maintaining thermal comfort level.

2. Methodology

Initially, a field survey was conducted in selected classrooms, which included both measurements of climatic parameters (indoor and outdoor) and the assessment of thermal comfort levels using the ASHRAE thermal sensation scale through a questionnaire survey conducted among the school children. The thermal comfort levels in the school classrooms were assessed during the peak hot and humid period of the year in 2022.

2.1 Climatic conditions

Sri Lanka is traditionally classified into three major climatic zones (i.e., dry, wet, and intermediate zones). The thermal comfort levels of the naturally ventilated school buildings in the South-Eastern region of Sri Lanka, which is in the dry zone were assessed in this study. The region is subjected to two annual climatic seasons, (1) peak hot and humid period from March to August and (2) North-East monsoon rainy season from September to February. The selected school buildings: (1) Mahmud Ladies College, Kalmunai (girls’ school) and (2) Zahira College, Kalmunai (boys’ school) are in the Kalmunai Zonal Educational Division.

2.2 Characteristics of school buildings and classrooms

The students in three classrooms in each school were selected for the thermal comfort survey. The selected classrooms are in a three-story naturally ventilated school building. These three-story buildings are typical of Sri Lankan school infrastructure systems, which are built with similar configurations and styles across the country. The selected classrooms are located on each floor of the three-story building. The typical floor area of a classroom is about 38 m^2, and nearly thirty to forty students’ study in a classroom. Figure 1 shows the configurations and indoor setup of the selected classrooms in this study.

Figure 1: Building pattern and classroom environment in the school selected for this study.

2.3 Measurement of indoor and outdoor weather parameters

A solar-powered wireless weather monitoring device was used to measure the weather parameters (indoor and outdoor) on the school premises. The weather parameters measured in this study include outdoor air temperature, indoor air temperature, and indoor relative humidity. The weather station (Figure 2a) was used to measure the outdoor air temperature, while indoor air temperature and relative humidity were measured using thermos-hygrometer sensors (Figure 2b). The sensors were wall-mounted (in each classroom) at a height between 2.0 to 2.5 m. The parameters were recorded at the interval of 30 minutes in the data logger (Figure 2c).

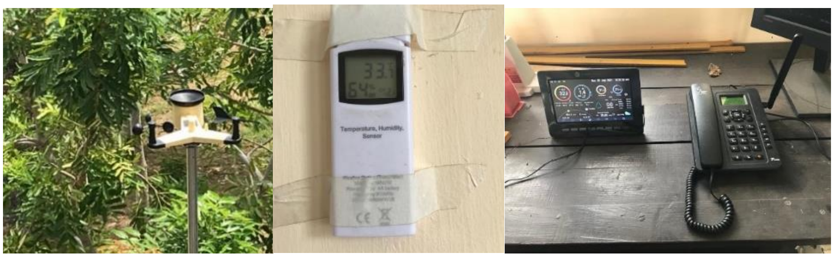

Figure 2: Instruments to be used in this field study; (a) Ambient Weather WS-2000 OSPREY Weather Station (b) Thermo-hygrometer sensor (c) Datalogger.

The global temperature was considered equal to the air temperature due to the high correlations observed between both parameters in naturally ventilated classrooms under hot and humid conditions (Talukdar et al., 2020; Zaki et al., 2017). The value of air movement, when the fans are operating inside the classroom was assumed as 0.7 ms^{-1} (Talukdar et al., 2020). When there was no fan in the classroom, it was assumed as 0.1 ms^{-1} (De Dear et al., 2015).

The metabolic rate is defined by the unit MET. A value of 1.2 MET was fixed for the metabolic rate from the standards, which corresponds to the seated office activities including seated reading, writing, typing, and seated filing (ANSI/ASHRAE Standard 55-2010, 2010). The clothing insulation was defined by the unit *clo*. Uniforms of students in the girls' school consisted of a full sleeve frock, Wardha (a type of scarf), trousers, and shoes, and the boys' uniform included a short sleeve shirt, trousers, shoes, cap, and tie. Since the uniform worn by girls has not been specified in the standards, a value of 0.8 *clo* was assumed based on the study conducted by Haddad et al. (2017) in Iran. A value of 0.6 clo was defined for boys' uniforms from the values given by ANSI/ASHRAE Standard 55-2010 (2010).

2.4 Thermal Comfort Questionnaire

A questionnaire was developed to evaluate the student's responses regarding thermal comfort levels in the classrooms. The questionnaire consisted of four main parts (1) general information (e.g., gender, clothing, position), (2) temperature preference (3) preference for air movement, and (4) students' tiredness level. For the collection of temperature preference data, the ASHRAE seven-point thermal sensation scale (ANSI/ASHRAE Standard 55-2010, 2010), five-point thermal preference scale, seven-point thermal comfort scale (Talukdar et al., 2020) and binary thermal acceptance scale (Mishra & Ramgopal, 2015; Singh et al., 2018) were included. All the possible adaptive actions that could be performed by the students were included as options in the questionnaire.

The population of each school varied between 2,500 - 3,000, where a building consists of around 120 students on each floor. 30 students were selected as representative random samples from the classroom on each floor. In total, 853 responses (428 males and 425 females) were collected from students aged between 16 to 19.

The questionnaire survey was conducted on several selected days over a period of five months (March-July 2022). The data were collected at three different time slots: 08:30, 11:30, and 13:30 Hrs. in each classroom, separately. An equal number of responses were maintained from each floor for valid comparison. The duration of each study period was around 40 minutes. The questionnaire was conducted during the last ten minutes of the period (i.e. thirty minutes after the period starts) to maintain the activity level and to ensure that the subjects were adapted to the thermal environment.

3. Results and discussion

Both the qualitative and quantitative results obtained were correlated and the key outcomes from the measurements and the survey are discussed in this section.

3.1 Environmental variables

The indoor air temperature (T_a) exhibited fluctuations between 27.7°C and 35.1°C, with a mean value of 30.5°C (SD = 1.8°C). In contrast, indoor relative humidity ranged from 60% to 86%, with a mean value of 75.8% (SD = 6.6%).

The outdoor temperature is a significant factor that influences the comfort temperature perceived by occupants in the adaptive thermal comfort approach. To incorporate the outdoor temperature, the running mean temperature (T_{rm}) was used in this study, which is the exponentially weighted average temperatures for seven previous days to the desired one (Udrea et al., 2016). The calculated running mean temperature ranged between 29.9 ºC and 31.7 ºC with a mean value of 30.6 ºC (SD = 0.8 ºC). In this study, the operative temperature (T_{op}) was adopted as the suitable thermal comfort index, since it was recommended by the standards (ANSI/ASHRAE Standard 55-2010, 2010). Nevertheless, certain assumptions were made regarding the globe temperature and air velocity in this study, as outlined in section 2.3. The resulting operative temperature ranged from 27.7°C to 35.1°C (mean = 30.5°C, SD = 1.8).

3.2 Analysis of subjects' thermal responses

The mean thermal sensation vote (*TSV*) in the morning (8:30 h), mid-day (11:00 h), and afternoon (13:30 h) were +0.04, +1.25, and +1.26, respectively. The above findings indicate that the prevailing environment had been neutral in the morning and moved towards warm in the afternoon. These results are further proved by considering the maximum students' *TSV* in each session; neutral (39.6 %) in the morning, slightly warm (41.1 %) in mid-day, and warm (26.4 %) in the afternoon.

The mean *TSV* on the ground floor, first floor, and second floor were +0.85, +0.76, and +0.82 respectively. Moreover, most of the students voted for "Slightly warm" (25.7 %), "Slightly warm" (31.7 %), and "Neutral" (28.4 %) on each floor respectively, which indicates that the prevailing environment had been slightly warm on each floor of the building.

Figure 3a shows the distribution of overall *TSV* results of the students, where the mean *TSV* was +0.81, and most of the students voted for "Slightly warm" (27.4 %), which indicates that the prevailing environment of the classrooms was slightly warm. Meanwhile, no students voted for cold sensation whereas, most students (68.5 %), voted for the comfort bands (-1, 0, +1) of the *ASHRAE* thermal sensation scale and two central comfort bands (0 & +1) occupied 52.4 % of the students' *TSV* votes. Whilst only 29.6 % of the students voted for cool (-3, -2, -1, and half of 0) and the remaining 70.4 % (half of 0, +1, +2, +3) of students chose warm when they were asked about the thermal sensation inside the classroom.

Figure 3b displays the distribution of overall thermal preference votes (TPV) among the students. The majority of students (65.8%) preferred a slightly cooler environment, while others opted for much cooler (14%), no change (15.5%), and slightly warmer (4.3%) conditions, respectively. The mean *TPV* was -0.89, which further proved that the majority of the students' *TPV* and the mean *TPV* are the same (i.e., slightly cooler).

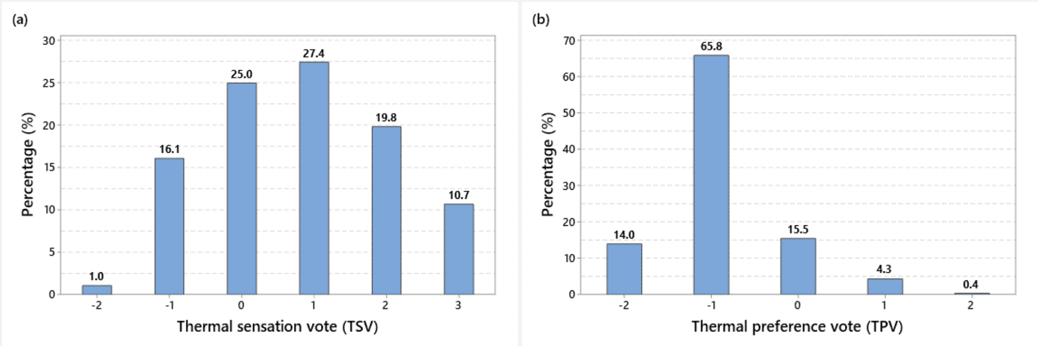

Figure 3: Distribution of students' responses; (a) overall thermal sensation and (b) thermal preference votes.

In general, most of the students felt just right (24.0 %), when they were asked about the comfort of the prevailing environment of the classrooms. However, the percentage of the votes for "Slightly comfortable" and "Slightly uncomfortable" is 23.8 % and 22.5 % respectively. 42.4 % of the students felt an uncomfortable environment (-3, -2, -1), and 57.6 % of the students felt a comfortable environment (0, +1, +2, +3) in the school buildings. Furthermore, the classroom environment was accepted by over half of the students (54.5%), whereas 45.5% of the students did not accept it. Based on the findings, it can be concluded that despite the warmer surrounding environment, more than half of the students felt comfortable.

3.3 Analysis of Thermal Sensation Votes

In this study, a regression analysis was used to obtain the neutral temperature (T_n) and comfort range. The average comfort temperature (T_{comf}) was found using Griffiths, (1990) method as it has been shown appropriate for a small number of samples (Talukdar et al., 2020).

3.3.1 Analysis of thermal sensation vote and operative temperature

The linear regression of thermal sensation vote (TSV) as a function of indoor operative temperature (T_{op}) is given in Eq. 1. Figure 4a illustrates the results of the linear regression analysis conducted between thermal sensation vote (TSV) and indoor operative temperature (T_{op}).

$$TSV = 0.3944\, T_{op} - 11.23 \quad (\mathrm{N} = 853,\ \mathrm{R}^2 = 0.31,\ \mathrm{p} < 0.001) \qquad (1)$$

The linear regression equation (Eq. 1) found significance with a p-value of less than 0.001. The neutral temperature (T_n) obtained for the entire sample was 28.5 °C, when TSV is 0. The comfort temperature range corresponding to thermal sensation votes -1 and +1 was between 25.9 °C and 31.0 °C. However, the linear regression model was found to be more suitable for air-conditioned buildings than naturally ventilated buildings (Talukdar et al., 2020).

3.3.1 Determination of comfort temperature

The comfort temperature (T_{comf}) was calculated using Griffith's equation (Eq. 2).

$$T_{comf} = T_{op} + \frac{(0 - TSV)}{\alpha} \qquad (2)$$

Griffith's constant (α) was assigned as 0.5 based on the past studies (Nicol & Humphreys, 2010; Singh et al., 2018). The average comfort temperature was found as 28.9 °C in this study, as represented in Figure 4b. The Griffith's comfort temperature ranged between 23.2 °C and 35.8 °C with a standard deviation of 2.1 °C. This finding shows that the average comfort temperature (T_{comf}) found using Griffith's equation (Eq. 2) is close to the regression neutral temperature (28.5 °C).

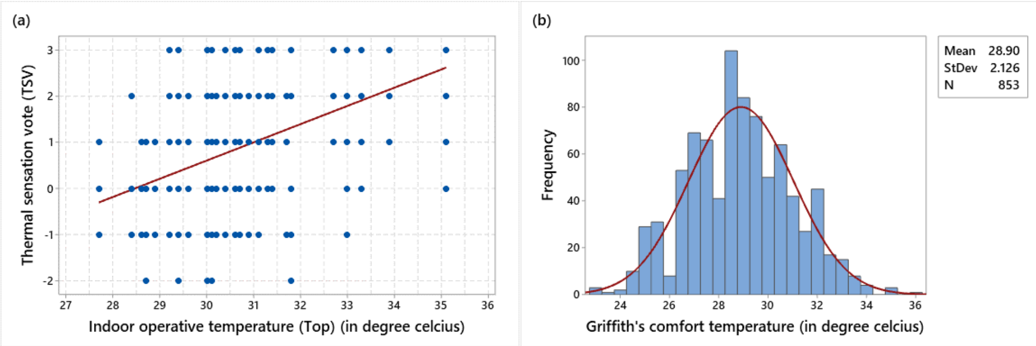

Figure 4: (a) Regression analysis between thermal sensation vote and operative temperature (b) frequencies of Griffiths comfort temperature.

3.4 Gender-based adaptive strategies of school students

Most of the girls preferred to switch on /increase the fan speed as an adaptive strategy on all floors (ground floor- 29.6 %, first floor- 38 %, second floor -36.2 %). Walking indoors/outdoors and drinking water are the next two most preferable adaptive strategies chosen by them. Ground-floor students had chosen opening windows as the third most preferable adaptive strategy (16.2 %). Switching on/increasing the fan speed, walking indoors/outdoors, and drinking water themselves occupy the third quarter of the preferred adaptive strategies on each floor (Ground floor-76.2 %, first floor-79.5 %, second floor-74.5 %).

The analysis of the adaptive strategies of boys shows that opening windows was the most preferred adaptive strategy (39.4 %) of the ground floor students, while other floor students chose walking indoors/outdoors (first floor-36.6 %, second floor-39.6 %) as the most preferred adaptive strategy. A considerable percentage of students had chosen each adaptive strategy provided. Comparing both schools, the most common activities were switching on /increasing the fan speed and walking indoors/outdoors.

3.5 The adaptive thermal comfort model

The adaptive thermal comfort model can be defined by linearly regretting indoor comfort temperature (T_{comf}) with an outdoor running mean temperature (T_{rm}). Figure 5 shows the linear regression analysis between Griffith's comfort temperature (T_{comf}) and running mean temperature (T_{rm}). In this study, the indoor comfort temperature open ture (T_{comf}), calculated using Griffith's equation (Eq. 2), was regressed against the outdoor running mean temperature (T_{rm}) to obtain the adaptive comfort model, as depicted in Eq. 3:

$$T_{comf} = 0.3484\, T_{rm} + 18.83 \ (N = 853,\ R^2 = 0.021,\ p < 0.001) \quad (3)$$

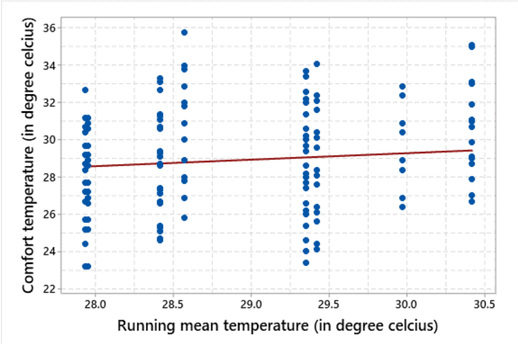

Figure 5: Linear regression analysis between Griffith's comfort temperature and running mean temperature.

The coefficient of determination (R^2) was obtained as 0.021. Despite the low value for R^2, the result was found significant in terms of p (< 0.001) value. Since the study was conducted to assess thermal comfort conditions during the critical period, when the climate was hot and humid, a lower value of R^2 was obtained.

Furthermore, the slope of the regression equation in this study is 0.35, slightly higher than the existing adaptive thermal comfort models, such as the CEN standard EN1525 (CEN EN 15251: 2007-08, 2012) and ASHRAE standard 55 (ANSI/ASHRAE Standard 55-2010, 2010) where the slope of the regression equations was 0.33 and 0.31, respectively. This finding can be interpreted as the students in the study climatic conditions are more sensitive to outdoor temperature changes than predicted by the existing standards. Singh et al. (2018) made a similar observation in naturally ventilated classrooms during the summer season in the composite climate of India; however, the slope of their regression equation was 0.49.

A slope of 0.38 was obtained in the study conducted by Talukdar et al. (2020) in Bangladeshi university classrooms during the hot and humid summer season. In the study by Singh et al. (2018), it was stated that occupants' adaptation to the thermal environment was also affected by people's culture, living habitat, preferences, and expectations other than the outdoor air temperature. Respondents performed several adaptive actions to overcome severe indoor environmental conditions.

Moreover, the comfort temperatures, which were calculated using ASHRAE Standard 55 adaptive model (ANSI/ASHRAE Standard 55-2010, 2010) fluctuated between 26.5 °C and 27.2 °C with a mean value of 26.8 °C, which is comparatively lower than the comfort temperature (28.9 °C) found using Griffith's model (Griffiths, 1990). These findings suggest that students adapt to higher outdoor temperatures than adults in the study context.

4. Conclusion

This study presented the findings of thermal comfort level assessments conducted in naturally ventilated classrooms of schools located in the Southeast coastal region of Sri Lanka during the peak summer season.

The results of this study indicated that students' thermal sensations moved from neutral in the morning to warm in the afternoon with the increase in outdoor/indoor temperature. More than half of the student population felt comfortable in the prevailing environmental conditions. The study identified a neutral temperature of 28.5 °C and a comfort temperature range of 25.9 °C – 31.0 °C for *ASHRAE* thermal comfort bands. The average indoor comfort temperature obtained using Griffith's method in naturally ventilated classrooms was 28.9°C, indicating proximity to the neutral temperature.

Regarding the adaptive strategies, a preference for fans was observed. Furthermore, the slope of the adaptive equation proposed by this study was found to be closer to the adaptive comfort equations put forth by existing thermal comfort models.

It was further observed that students prefer to be more thermally comfortable in these naturally ventilated classrooms. Apart from the prevailing climatic conditions, students were highly adapted to these extreme climatic conditions. Since a large student population occupies the school buildings during the daytime, structural engineers and architects need to design new classrooms or modify existing classrooms to provide a better thermal comfort level.

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ICSBE 2023-167

FRAGMENTATION ANALYSIS OF PERI-URBAN NATURAL ECOSYSTEM; THE CASE OF BAHIRAWAKANDA TERRAIN, KANDY, SRI LANKA

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Abstract: Development impact on natural ecosystems is especially a major problem in the developing world. This is mainly due to the rapid urban developments and inadequate concern for managing natural ecosystems. Urban and peri-urban natural terrain ecosystems are the most vulnerable ecosystems, facing this predicament. This research investigates, using the remote sensing field, the ecological deterioration due to the neglect of natural terrain in the rapid urbanization process. In Sri Lanka, the field of remote sensing is not widely applied in analyzing urban issues. The study focuses on understanding and calculating the ecological impact concerning Kandy Bahirawakanda's natural peri-urban terrain ecosystem based on a remote sensing field. Four ecological impact indexes can be used to measure the impact using remote sensing technology. This paper uses the ecological patch fragmentation index as the measuring device to measure the increase in fragmentation of ecological patches. This approach provides a clear insight into how a singular ecological patch fragments into separate patches and the increase of gaps between those patches. This provides a very good physical and visual indication of one important aspect of the destruction of natural ecosystems. This is very much pertinent to the current Sri Lankan context as peri-urban developments, especially new residential developments/urban planning and subdivisions are carried out with little regard to ecological integrity in the area. While there is some protection for government-identified ecological reserves there is practically no identification or protection for the general integrity and health of the broader ecological network of an area.

Keywords: Patch fragmentation; Patch isolation; Peri-urban; Natural ecosystems; Remote sensing

1. Introduction

Rapid and unnecessary urban expansion in the last few decades has caused a massive decline and even total loss of connectivity in Urban terrain landscapes leading to challenges (Kowe et al., 2021) in maintaining good Urban natural ecosystems. These ecosystems are vital for the urban population and the environment and fulfill a variety of useful ecological tasks. For example, these systems may mitigate the heat island effect, provide a habitat for local flora and fauna, and provide soothing vistas for the inhabitants. However, in some urban areas, these ecological clusters are becoming more and more isolated, less dense, and declining in size due to the effects of transit network developments and. legal and illegal encroachments due to property developments (Ranaweera et al., 2021). These threats will lead to problems in the balance of urban terrain Ecosystem Biodiversity, environmental conditions, and urban microclimate (Wijayawardana et al., 2020). Of these urban areas, peri-urban areas are the most vulnerable as they still retain significant ecosystems that face development pressure.

Therefore, it is important to analyze this impact. There are four ecological impact indices (increased patch isolation, edge effects, impact of fragmentation, and habitat buffer) that can be used to measure the deterioration of peri-urban natural ecosystems using remote sensing technology(Spiesman et al., 2018). This paper analyses the impact of fragmentation using the edge effect index as the measuring device to measure the increase of isolation of ecological patches. This approach provides a clear insight into how a singular ecological patch fragments into separate patches and the increase of gaps between those patches.

2. Literature Review

2.1Peri-urban natural ecosystems

While there is no universally accepted definition, peri-urban areas are often defined as transitional zones between rural and urban areas, where the characteristics of both commonly overlap. These areas, for example, feature a wide range of land-use patterns, from agricultural and forestry to residential and industrial applications. Natural Ecosystems in these regions are called peri-urban natural ecosystems (figure 2). ("CDKN-PB-Peri-urban-ecosystems-India_Web.pdf," n.d.)

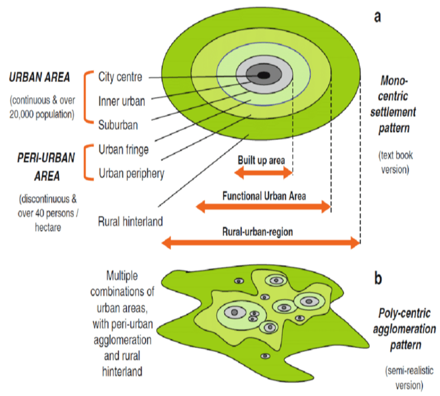


Figure 1: Concept of peri-urban areas and the rural–urban-region *(Source: Idczak & Mrozik, 2018)*.

Peri-urban environments, which can feature valuable protected biotopes, preserved woods, prime agricultural fields, and significant wetlands often provide crucial ecosystem services for city dwellers (Douglas, 2006). From an economic, environmental, and social perspective, peri-urban areas represent very complex territorial spaces. However, despite their complexity, both urban and peri-urban inhabitants rely on the various peri-urban ecosystem services that these places provide (Lee, 2015).

2.2Impact on peri-urban natural ecosystems due to rapid urbanization

Natural resource consumption in peri-urban areas is increasing due to fast urbanization and increased human activity, putting peri-urban ecosystems at risk of deterioration and loss. (Degradation-and-Loss-of-Peri-Urban-Systems.Pdf, n.d.) The influence of urban growth on peri-urban ecosystems varies depending on whether growth is characterized by expanding sprawl or increasing population density in these are Degradation-and-Loss-of-Peri-Urban-Systems.Pdf, n.d.). Urban areas do not function in isolation, but rather as part of a "sphere of dependency" on their surroundings and ecosystems. As a result of the degradation of these ecosystems, ecosystem services that support urban and peri-urban populations are lost.

2.3Impact of fragmentation

Natural forces and human activities, both acting over different time frames and spatial sizes, generate fragmentation. According to Gibbs' theory (Laverty and Gibbs, n.d.), fragmentation leads to a reduction in patch size, an increase in edge effects, and an increase in patch isolation. The assertion could prove that fragmentation leads to changes in the organization of urban ecological networks. Early hunters shaped the terrain by burning areas to benefit certain game species, and ranchers do the same today. Agriculture, habitation (e.g., erecting fences, etc.), resource extraction (e.g., mining, timber), and industrial growth (e.g., the construction of hydroelectric dams) are all examples of human activities that alter and fragment landscapes. Agriculture, among these activities, is the primary source of ecosystem loss and fragmentation in much of the world. (Laverty and Gibbs, n.d.)

2.4Theoretical framework and research methodology

The analysis has been done by monitoring three selected ecological patches by using remote sensing and geographic information system (GIS) over 20 years in the selected area, from 2000 to 2020. The increased patch isolation index as explained in the literature review is used to analyze the selected area. The remote sensing field method was used as the primary analysis method as it has the least-cost path for an analysis of this nature with some inaccessible places. Three components of the impact of fragmentation (Figure 2) are used as the measuring tools. Relevant formulas and calculations are shown in the case study section.

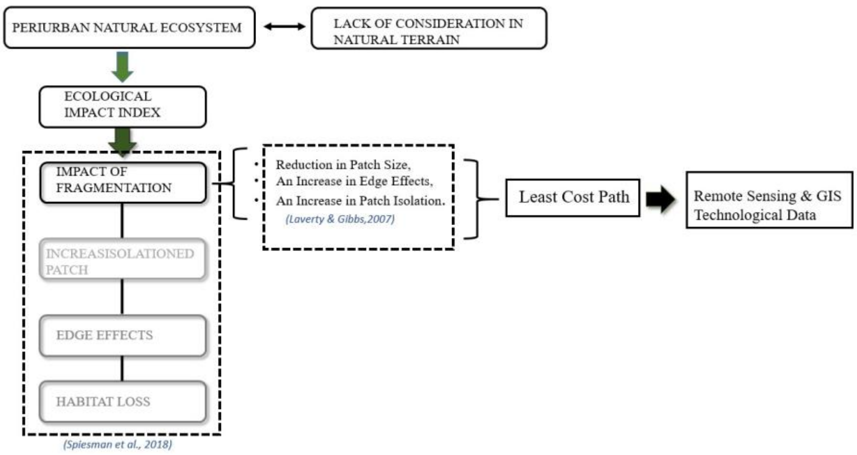


Figure 2: Theoretical Framework Chart (Source: Compiled by Author).

The methodology of the study is formulated (Figure 3) by considering the previous studies done on a similar subject and the type of data needed for the analysis of the study. Remote sensing software is used to analyze and generate main data.

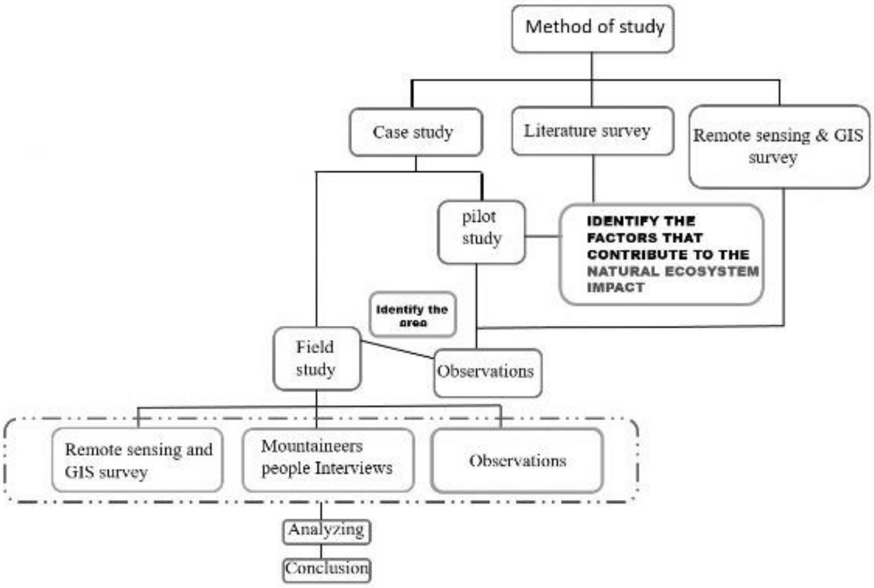


Figure 3: Research Methodology Chart, (Source: Compiled by Author).

The study consists of three components: peri-urban natural ecosystems, ecological impact index, and peri-urban natural ecosystem impact. To complete the analysis these three components, have to be addressed. The First task of the study is to identify peri-urban natural ecosystems from the Sri Lankan context as the case study. The second step is to identify the ecological impact index which is suitable for the analysis. The final step is to quantify the peri-urban natural ecosystem impact using remote sensing.

3 Data Presentation of the Case Study Analysis

3.1 Case Study

Bahirawakanda is a natural terrain consisting of peri-urban natural ecosystems which are in the vicinity of Kandy town. During the last two decades, the ecosystem of this area bore the brunt of the effects of the rapid urbanization process in the Kandy city area. Two and half Square kilometer ($2.5km^2$) area in Bahirawakanda is chosen for this investigation (Figure 4). The area was limited to this patch only due to time and accessibility constraints which did not allow further investigations into adjoining several patches.

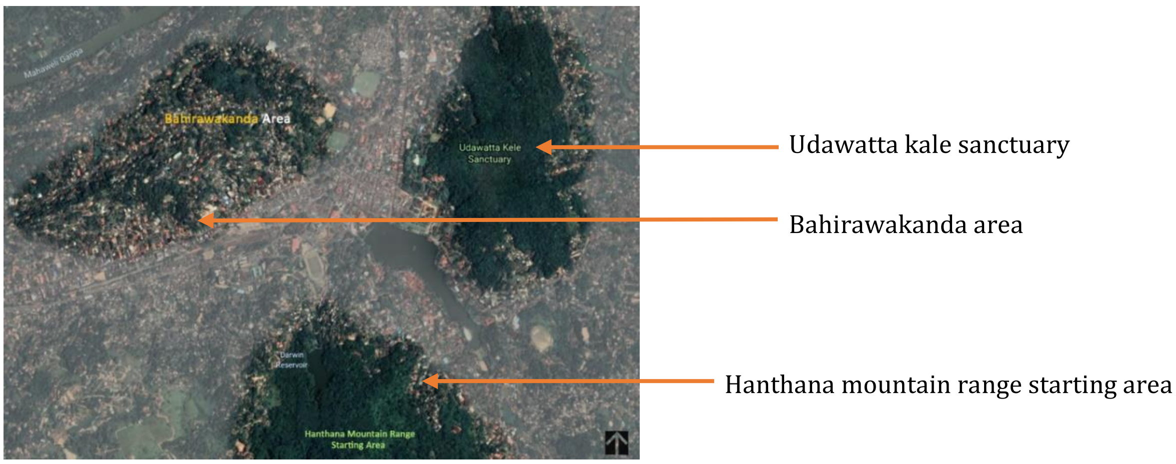


Figure 4: Case study selection criteria (Source: compiled by author).

3.1.1 Impact of fragmentation

Impact of fragmentation

- Reduction in patch size
- Increasing in edge effect
- Increasing patch isolation

3.1.1.1 Reduction in patch size, increase in edge effect, and increasing patch isolation

There were no large fragmentation regions detected on the 1935 land use map. Then, looking back over the last two decades, three large ecological fragmentation areas could be detected between 2000 and 2005(Pa1, Pa2, Pa3). At that time Pa1 was facing the internal fragmentation (F1) process.

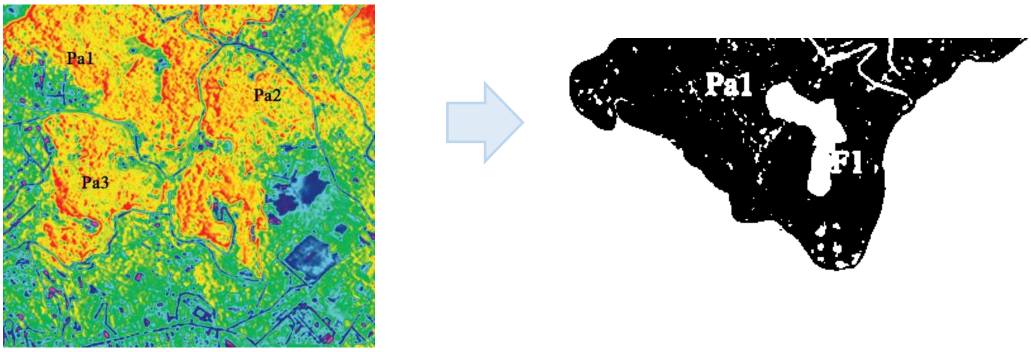


Figure 5: Bahirawahannda Area Landsat Remote Sensing data: Image 2005
(Source: RS data through compiled and edited by author).

This section examines the three factors mentioned above that have a direct effect on the impact of fragmentation in deleted areas. Furthermore, because it is easier to process as a collection, these three aspects are analyzed as a group. However other impact indexes' aspects are analyzed separately.

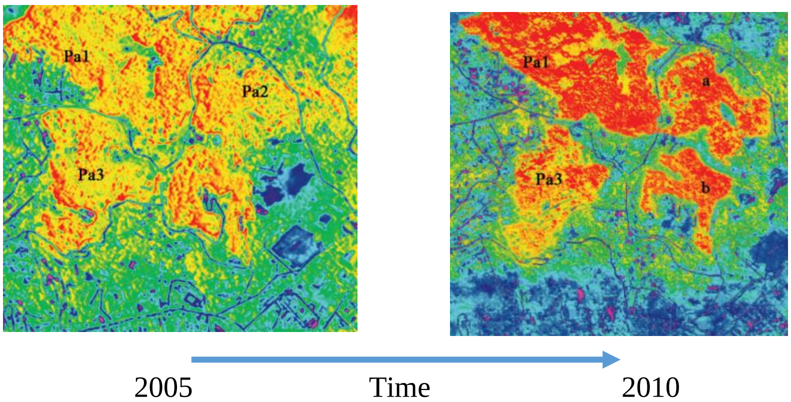
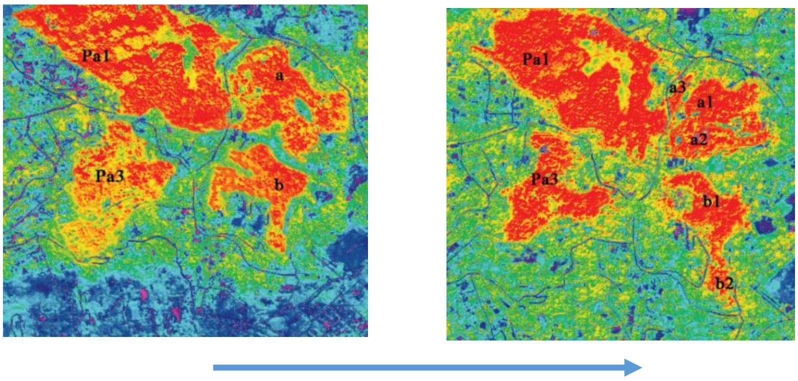
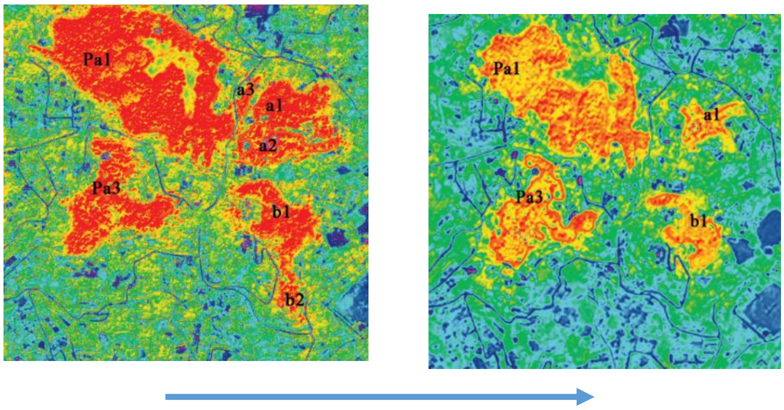


Figure 6: Bahirawahannda Area Landsat RS data: Image 2005-2010
(Source: compiled & edited by author).



2010 Time 2015

Figure 7: Bahirawahannda Area Landsat RS data: Image 2010-2015
(Source: compiled & edited by author).



2015 Time 2020

Figure 8: Bahirawahannda Area Landsat RS data: Image 2015-2020
(Source: compiled & edited by author).

Considering the past two decades, from 2005 to 2020, identifying Pa1, Pa2, and Pa3 ecological patch sizes started to decrease.

3.1.1.1.1 Pa1 ecological patch

Considering the Pa1 ecological patch, the F1 internal fragmented area has increased, which directly contributes to the internal patch reduction.

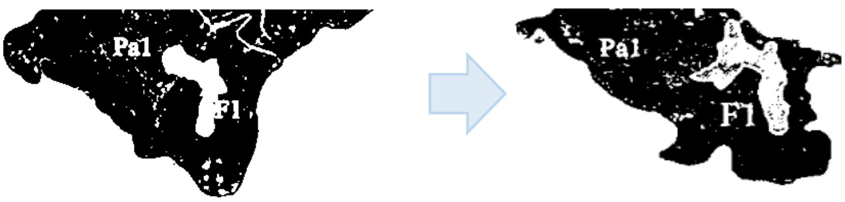


Figure 9: from 2005 to 2010 Pa1 ecological patch decreased Remote Sensing land sat data (Source: Landsat Remote sensing data compiled by author).

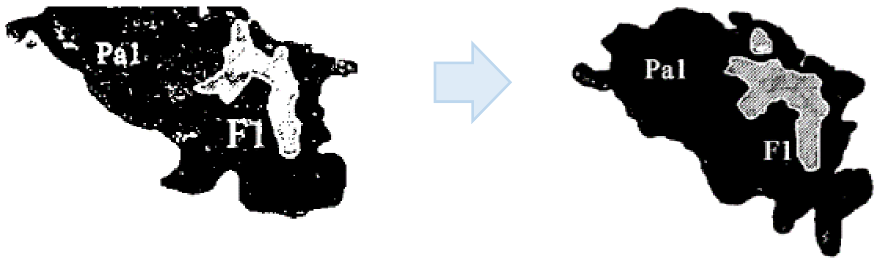


Figure 10: from 2010 to 2015Pa1 ecological patch decrease Remote Sensing land sat data (Source: Landsat Remote sensing data compiled by author).

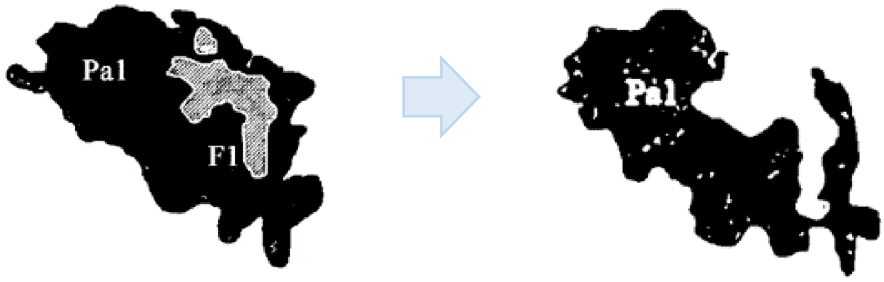


Figure 11: from 2015 to 2020 Pa1 ecological patch decrease Remote Sensing land sat data (Source: Landsat Remote sensing data compiled by author).

3.1.1.1.2 Pa2 ecological patch

Considering the Pa2 ecological patch, from 2005 to 2010 can be identified two fragmented areas and b. at that time "a" area was facing internal fragmentation. (Fa1, Fa2, Fa3, and Fa4) From 2010 to 2015 internally fragmented areas were increasing. As a result, that "a" area fragmented as a1, a2, and a3. Furthermore "b" area is fragmented as b1 and b2. As a result of previous years, the size of the pa2 ecological patch declined rapidly from 2015 to 2020

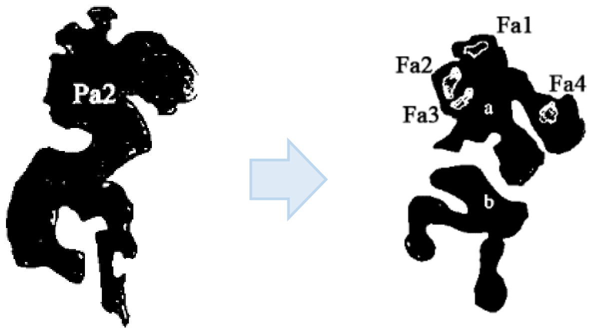


Figure 12: from 2005 to 2010 Pa2 ecological patch decreased Remote Sensing land sat data (Source: Landsat Remote sensing data compiled by author).

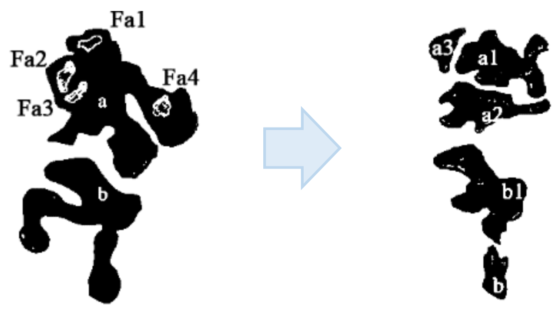


Figure 13: from 2010 to 2015 Pa2 ecological patch decrease Remote Sensing land sat data (Source: Landsat Remote sensing data compiled by author).

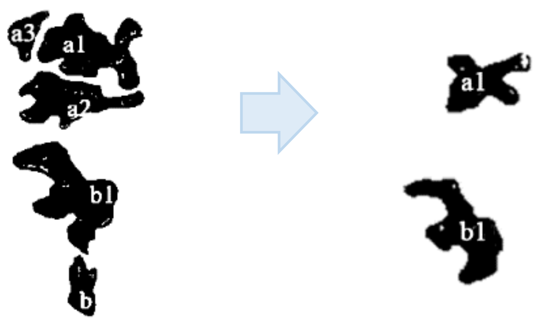


Figure 14: From 2015 to 2020 Pa2 ecological patch decrease Remote Sensing land sat data. (Source: Landsat Remote sensing data compiled by author)

3.1.1.1.1 Pa3 ecological patch

Considering the Pa3 ecological patch, there were no fragmented areas in 2005. After that from 2005 to 2020 can be identified internal fragmented areas and the boundary decrease of the Pa3 ecological patch can be identified. Because of that patch size was decreasing.

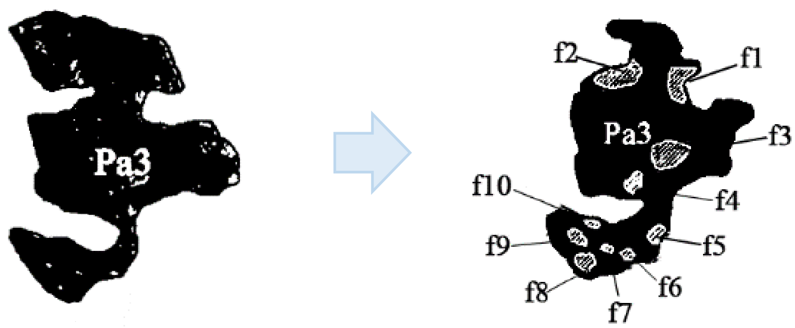


Figure 15: From 2005 to 2010 Pa3 ecological patch decreased Remote Sensing land sat data (Source: Landsat Remote sensing data compiled by author).

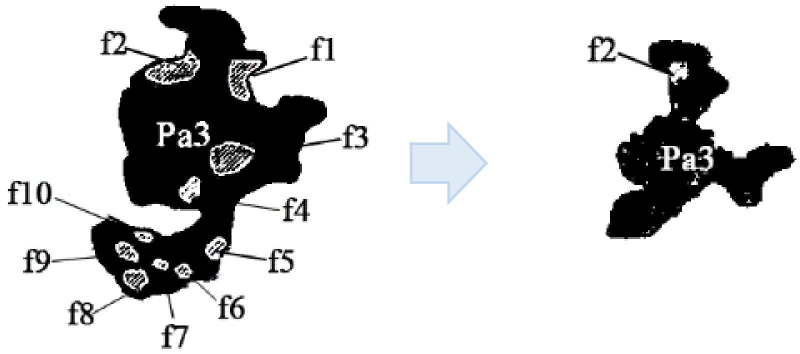


Figure 16: From 2010 to 2015 Pa3 ecological patch decrease Remote Sensing land sat data (Source: Landsat Remote sensing data compiled by author).

Figure 17: From 2015 to 2020 Pa3 ecological patch decrease Remote Sensing land sat data (Source: Landsat Remote sensing data compiled by author).

Based on the aforementioned data, the pa1, pa2, and pa3 ecological patches appear to have been fragmented. Furthermore, the graph following demonstrates it.

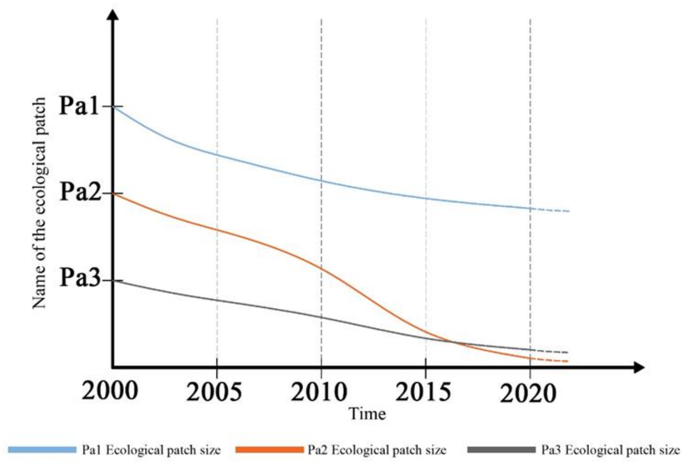


Figure 18: The illustration of three major ecological patches in the selected area has been reduced. (Source: Above data through, compiled by author).

Considering Figure 17, in 2000 Pa1 ecological patch size was higher than other main patches. Furthermore, the rapidity of the decline in Pa1 size from 2000 to 2010 was higher than the rapidity of the decline in Pa1 size from 2010 to 2020. In the year 2000, the Pa2 ecological patch was larger than the Pa3 patch but smaller than the Pa1 patch. The rapidity of decline in Pa2 patch size has been higher than the other two patches since 2010. Between 2015 and 2020 nearly 2016, the rapidity of decline in Pa2 and Pa3 ecological patch sizes were equal. After that situation, the rapidity of decline in pa2 patch size was extremely high. By 2020 it is higher than the rapidity of decline in the Pa3 patch size. That is, by 2020 Pa2 patch size was decreased than the other two patches because of the fragmentation.

Plot area ratio

$$\frac{\text{Build area}}{\text{Total land area}} \times 100\% \qquad \textbf{(1)}$$

Equation 1-Plot area ratio (Source: UDA provincial office Kandy)

Taking the above equation into consideration, when the total land area (selected land area = 2.5 square kilometers) is constant, the plot area ratio increases as the build area increases. Therefore, the plot area ratio graph of the selected area, including the three ecological patches (Pa1, Pa2, and Pa3), can be presented as follows.

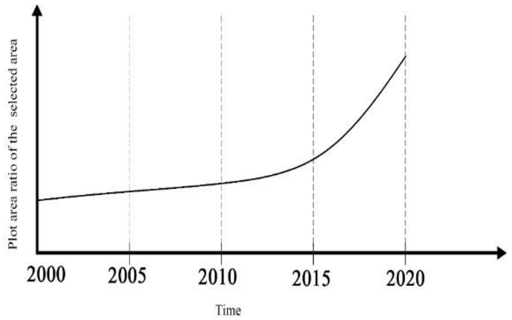


Figure 19: Illustration of the changes in plot area ratio (built area increases) from 2000 to 2020. (Source: Above data through, compiled by author).

4. Results

In considering the analytical data by the three main factors of section 3.1.1,

Analysed factors / Name of the patch	The entire edge effect	The entire patch size	The entire patch isolation
Pa1	Comparatively much low ↓	Comparatively much high ↑	Comparatively low ↓
Pa2	Comparatively much high ↑	Comparatively much low ↓	Comparatively much high ↑
Pa3	Comparatively high ↑	Comparatively low ↓	Comparatively high ↑

Based on the above findings, it can be concluded that if the total edge effect is low and the total patch size is large, the isolation of the considered patch is low. Its unique feature is that it may be used to determine the fragmentation of ecological patches in inaccessible regions remotely. Furthermore, this can be used to forecast future effects.

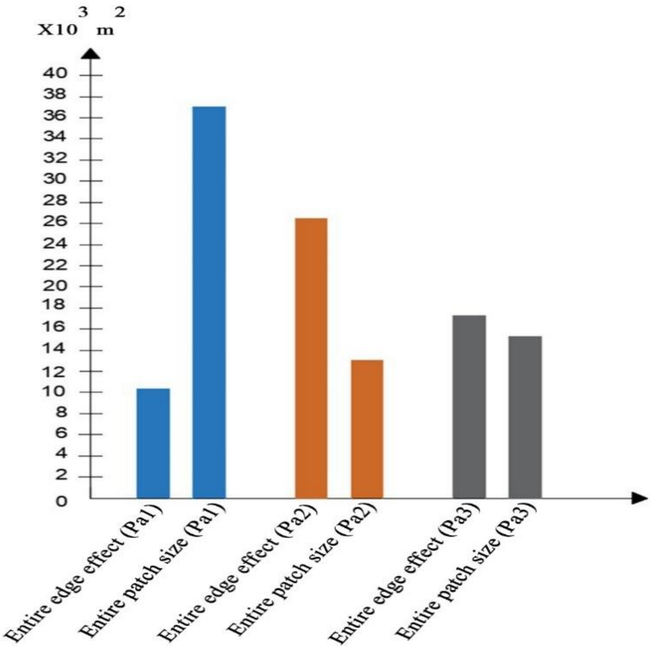


Figure 20: The chart shows the entire edge effect and entire patch size fluctuations of the main patches. (Source: Section 3.1.1 Analytical remote sensing data through, compiled by author).

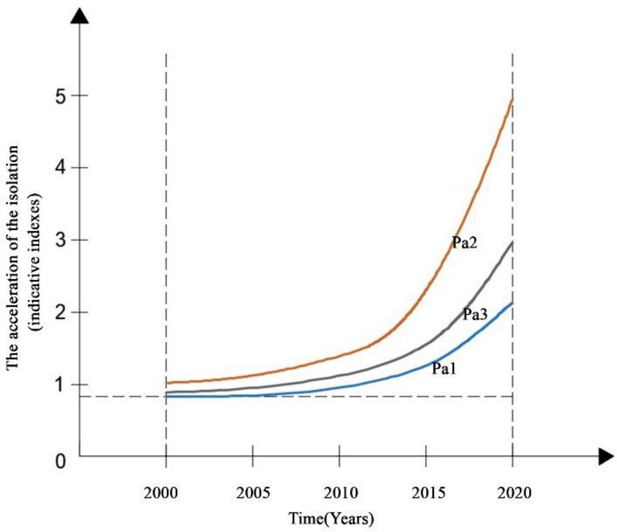


Figure 21: The chart shows the acceleration indicative indexes of the isolation of main patches, from 2000 to 2020. (Source: Chapter 3 Analytical remote sensing data through, compiled by author).

If the edge effect is very high, as seen in Figure 19, the patch size is considerably reduced. According to that, the lowest patch has a maximum acceleration of isolation (figure 20). Furthermore, can concluded that, if a patch has the maximum acceleration of isolation, it has the highest fragmentation. Furthermore, based on Figure 20, it can be predicted that the Pa2 patch will become much more fragmented.

5. Conclusion

According to this research, it is evidence that during the study period of twenty years (2000-2020), there was a significant negative impact on peri-urban natural ecosystems in terms of the impact of fragmentation. All three measured matrixes of the impact of fragmentation show a negative impact. This will have a deep impact not only on the ecology, wildlife, and soil condition but also on the habitats of the area. As this is also a hilly terrain fragmentation of the ecology may lead to additional impacts such as landslides.

This research also shows how the remote sensing field can be effectively used for analyzing issues in urban studies which is not extensively practiced in Sir Lanka. This is very much pertinent to the current Sri Lankan context as peri-urban developments, especially new residential developments and sub-divisions are carried out with little regard to ecological integrity in the area. While there is some protection for government-identified ecological reserves there is practically no identification or protection for the general integrity and health of the broader ecological network of an area. In the future, this type of remote sensing-based analysis can be effectively used as the starting point for identifying and protecting ecological regions or networks in urban and peri-urban areas in the future. This method has the further advantage of analyzing inaccessible and difficult ecosystems like glacier ecosystems, dense forests, montane forests, urban wetlands, etc.

Such outcomes shall be integrated into the development plan and proposal of an area or a region. This research was limited to analyzing only one aspect; namely the impact of fragmentation of the ecological indices and limited to a small area due to time and resource constraints. However, a more comprehensive knowledge of the impact on ecology can be obtained by carrying out further research on other ecological indices in combination with the impact of fragmentation on a much larger area.

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EXPERIMENTAL INVESTIGATION ON POROUS CONCRETE FOR SUSTAINABLE DRAINAGE SYSTEMS

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Abstract: Flooding in urban areas caused by unpredictable high-intensity rainstorm events due to a lack of sufficient drainage infrastructure has become a major problem nowadays. Urbanization and climate changes in urban cities have made drainage systems overflow, which results in urban floods. Introducing a sustainable urban drainage system is an effective solution to control urban floods. Furthermore, it will control downstream flooding and it will reduce the deterioration of river water quality. Porous concrete drainages can be a good alternative in urban areas as they can infiltrate excess runoff into the soil. In many countries, construction debris has become a severe environmental issue. So, it is an environmentally friendly approach to reuse or recycle construction wastes for the manufacturing of porous concrete. Porous concrete has already been used to create pavements, parking lots, and cover slabs. However, only a few researchers have studied different mix designs for porous concrete. This study is based on eight mix designs, which will be comprised of without fine aggregates and with fine aggregates mix designs. 12.5 - 25 mm coarse aggregate size weight was changed for the first 4 mix designs. The other 3 mix designs were comprised of fine aggregates and changed percentages of fine aggregates by 10%, 20% and 30%. A comparison of normal porous concrete versus construction waste porous concrete was studied as the final experiment. When the coarse aggregate percentages changed from 15% to 75%, infiltration rates increased from 133.6 inches/hr to 448 inches per/hr and the seven-day compressive strength varied from 14.3 MPa to 12.1 MPa. When fine aggregates were introduced from 10% to 30%, the compressive strength increased from 16.5 MPa to 18.21 MPa and the infiltration rates decreased from 600 inches/hr to 320 inches/hr. Test with construction waste yielded 16.28 MPa strength and 1400 inches/hr infiltration after 28 days showing its potential to be used in urban areas.

Keywords: Sustainable drainage systems; Porous concrete; Compressive strength; Infiltration rate; Urban flash flood controlling

1. Introduction

The world's population has surpassed the halfway mark and now resides predominantly in urban areas, with more than 500 cities accommodating over a million people each. The growing risk of floods in these urban settings, resulting from intense and unpredictable rainfall, has become a significant concern due to the combined impact of urbanization and climate change. The lack of suitable drainage infrastructure exacerbates this issue. Sustainable Urban Drainage Systems (SUDS) offer a solution by addressing environmental concerns related to urban runoff and the damage caused by pollutants. Among the SUDS options, Pervious Pavement Systems (PPS) and other hard SUDS are specifically designed to allow stormwater runoff to permeate and be absorbed by underlying layers. Moreover, PPS can also be utilized for auto parking, pedestrian traffic, and vehicular traffic (Mbanaso et al., 2019).

The improper disposal of construction waste has emerged as a global problem due to rapid urbanization, industrial expansion, and population growth. Unfortunately, more than 90% of construction waste is deposited in landfills, as the majority of countries lack efficient plans for reusing and recycling these materials in new construction endeavours (Bhutta et al., 2013). Examples of construction and demolition debris include bricks, concrete, soil, gravel, masonry, paving materials, lumber, shingles, glass, plastic, aluminium, steel, drywall, asphalt, plumbing fittings, wood or timber, cardboard, and so on. Porous concrete has been employed in various studies, primarily for the construction of parking lots. This type of concrete allows water to flow freely through its pores. However, limited research has been conducted on the use of porous concrete in urban drainage systems. Incorporating porous concrete into urban stormwater management systems can significantly contribute to the prevention of flash floods.

While pavements, parking lots, and cover slabs have been successfully constructed using porous concrete, the exploration of different mix designs for porous concrete remains scarce. This study examines eight mix designs, four of which include changes in the weight of coarse aggregate sizes ranging from 12.5 to 25 mm. The remaining three mix designs incorporate fine aggregates, with varying percentages of fine aggregates (10%, 20%, and 30%). The objective of this research is to utilize recycled aggregates from construction waste to produce porous concrete slab panels, thereby investigating the compressive strength and infiltration rates of porous concrete for different aggregate gradation curves within the same mix design ratio.

2. Literature Review

Numerous studies have explored the application of porous concrete in pavement designs, parking lots, and walking paths. Some research has focused on Sustainable Urban Drainage Systems (SUDS) and their role in drainage control. However, there is a scarcity of studies examining the use of recycled construction waste as aggregates in the production of porous concrete and its potential applications.

2.1 Sustainable Urban Drainage Systems

Traditional sewer-based systems have been in use for 150 years to improve cleanliness and prevent urban flooding. Sustainable Urban Drainage Systems (SUDS) have emerged as alternative or supplementary methods to these conventional systems in the past four decades. 'Green' alternatives such as green roofs, rain gardens, infiltration trenches, swales, and dry and wet basins have been introduced as part of SUDS (Zhou, 2014). It revitalizes the pursuit of sustainable urban ecosystems. However, there have been limited previous studies on using recycled construction waste as a method for SUDS. Therefore, this research focuses on developing an SUDS method based on porous drainage systems through the use of recycled construction waste materials.

2.2 Porous Concrete Drains and Pavements

Porous concrete is a mixture of coarse aggregate, Portland cement, and water that overlays a stone aggregate reservoir and allows for quick water infiltration. As runoff infiltrates into underlying permeable soils and/or out through an underdrain system, this reservoir provides temporary storage**.** It is used in a variety of applications that need permeability, noise absorption, or thermal insulation due to its high porosity. Porous asphalt and Porous concrete pavements are the most widespread and well-studied porous pavement materials (Chandrappa et al., 2016).

2.3 Porous Concrete Properties

In general, porous concrete has a low strength due to the large void ratio when recycled aggregates are used. Recycled aggregate porous concrete has a lower compressive strength than regular aggregate porous concrete. Clogging refers to a reduction in permeability in porous concrete. It can be caused by a variety of physical, chemical, and biological mechanisms (Kia et al., 2017). The physical blockage is the deposit of large particles on the surface or in the interior layers. Chemical blockage occurs when carbonate and sulphides in precipitated minerals partially or completely block pore spaces (Lin et al., 2016). Algae and bacteria produce a biological blockage. The hydraulic conductivity in porous media is reduced due to the penetration of plant roots that have been linked to the particles.

2.4 Porous Concrete Mix Designs and Gradation Curves

There were previous porous concrete mix designs in the literature. The methodology for this research was made according to those mixed design proportions and coarse aggregate gradation curves. For the coarse aggregate gradation curve, an optimum gradation limit for the pervious concrete road base material is as in Figure 1 (Yang et al., 2008).

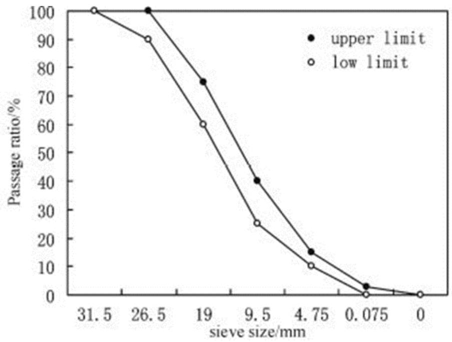

Figure 1: Optimum gradation limit.

The suitable content of 4.75 - 9.5 mm particles in coarse aggregate is around 20%. So, the porous concrete has enough strength and infiltration capacity. Pervious concrete with fine aggregates was studied for two mixed designs. Previous mortar gradation curves are as follows in Figure 2.

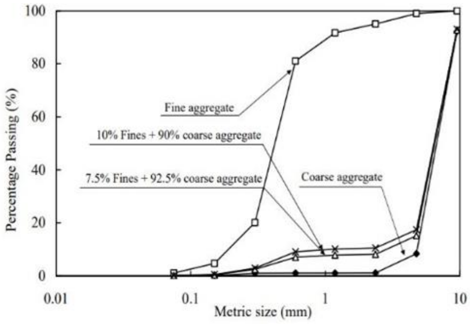

Figure 2: Pervious concrete gradation curves containing fine aggregates.

Two mixed designs were studied by Aoki (2009). Those were,

1) 1: 3.7: 0.3: 0.35 - Cement: Coarse: Fine: Water (7.5% fine aggregate)
2) 1: 3.6: 0.4: 0.35 - Cement: Coarse: Fine: Water (10% fine aggregate)

For different mix designs, water cement ratio was changed. The way of mixing and compaction methods were described in previous experiments. Experiments were followed by hand mixing and compaction was done by tamping rod without vibrations. The relationship between infiltration rate and compressive strength for the above mix designs was observed. In conclusion, previous concrete compressive strength ranges between 4 MPa and 19 MPa with an average of about 12 MPa and an infiltration rate average is about 1200 l/min/square meters (Gaurav et al., 2015). The aggregate gradation, which typically comprises of single-sized or a binary mixture of coarse particles, has a big impact on the pervious concrete qualities. Fine particles (less than 30% by weight of total aggregates) are added to boost the concrete's strength while gradually reducing the void content. Coarse aggregates range from 4.75 to 25 mm. To provide adequate coating for aggregates, the water-to-cement ratio (w/c) is normally between 0.28 and 0.40. The ideal w/c number for no-fines concrete mixtures is 0.30 (Perera et al., 2020).

2.5 Construction Waste

Construction and demolition trash has reportedly increased because of global urbanization and population development. According to some estimates, building destruction accounts for around 40% of global garbage (Jayasinghe et al., 2009). Recycling of Construction and Demolition Waste (CDW) is only attractive when the recycled product is competitive with natural resources in quality, cost, and quantity and then the best option is to reuse the CDW as construction materials. Recycling of construction waste can be done for broken concrete, building bricks, broken pavements, and other construction trash. Recycled aggregates can be obtained from building demolition, airport runways, and concrete roadbeds. Eco composite in porous concrete is designed with a mixture of concrete and a cement replacement. The eco composite has the element of waste material that is being recycled such as rice husk ash (RHA), eggshells, fly ash, wood waste ash and many more (Roach, 2001).

3. Methodology

There weren't many studies in the literature comparing the infiltration rates of different coarse aggregate gradation curves into porous concrete. Furthermore, there are only limited studies on porous concrete made from recycled construction materials. Hence, to conduct our research, a new approach was followed.

3.1 Porous Concrete Mix Designs

For porous concrete to operate at its best in terms of permeability, strength and durability, a proper mix design is crucial. The continuity of cement pastes with coarse aggregate embedded to maintain continuous voids is the most important criterion in the design of porous concrete. Generally, the aggregate-cement ratios (A/C) are in the range of 4 to 6 by mass. These A/C ratios lead to aggregate contents between 1300 kg/m^3 to 1800 kg/m^3. Higher A/C ratios have been used in laboratory studies but with significant reduction in strength. For the lab experiments, we used ACI Standards guidelines. The targeted compressive strength after 28 days was 15 MPa for porous concrete. According to that the appropriate mix design ratio was 1: 4.3: 0.3. The addition of water-reducing admixtures (ASTM C494 Type RHEOBUILD 1000) improved the porous concrete's workability and strength. As a result of the admixture addition and the use of recycled material, acceptable porous concrete with adequate drainage capacity and strength was produced. The mixed design plan was as follows (Table 1).

Table 1: Mix Design Plan

Mix Design No.	Description
1 - 4	Different 12.5 – 25 mm coarse aggregates % and no fine aggregates
5 - 7	10%, 20%, and 30% fine aggregates and the same coarse aggregate gradation curve
8	Construction waste aggregates used

In the first 7 mix designs, the aggregate gradation curves for normal coarse aggregates were changed and the mix design ratio was for Grade 15 porous concrete. The first 4 mix designs were done without fine aggregates. Different coarse aggregate gradation curves were used and mainly focused on the large particle size range, which was 12.5 - 25 mm. The next 3 mix designs were done with fine aggregates. Changed the fine aggregate ratios to 10%, 20% and 30% of the aggregate weight and used the same gradation curve for coarse aggregates. The final mix design was done to construction wastes.

3.2 Material Collection and Preparation

We collected construction waste materials from the university premises from a construction site at the Faculty of Engineering (Figure 3). Construction wastes were broken and crushed into aggregate part sizes we needed.

Figure 3: Construction waste collection.

Sieve separation was done to separate coarse aggregates into 4.75 - 9.5, 9.5 - 12.5, 12.5 - 19.5, 19.5 - 25 mm ranges. Coarse aggregate gradation curves were drawn for these ranges. Sieved aggregates were used for mixed designs in different proportions.

3.3 Casting of Porous Concrete Slab Panels

After making porous concrete, the infiltration testing and compressive strength testing for different mix designs were done. The ASTM standard methods were followed for the laboratory tests. For that, slab panels were cast. The slab panel dimensions used for the preparation of form works were length, width, and height as 50 cm, 40 cm, and 8 cm respectively.

Prepared formwork was placed on top of the soil. Then, the slab panel was cast from porous concrete. After preparing porous concrete, the casting of slab panels should be done. The slab panels were cast without on soil and soil. The most effective method was to cast on the soil as it prevented the accumulation of grout at the bottom. Figure 4 depicts.

the casting of porous concrete on soil. Compaction should be done when casting because it was proved effective in results.

Figure 4: Casted slab panel.

3.4 Lab Experiments and Testing

The study followed the standard ASTM C1701 test for infiltration test. For that, an Infiltration ring should be made to do the test as in Figure 5. The Diameter should be 300 mm and the height of the ring should be at least 5 cm. The Eq. (1), provided in ASTM C1701 was used to calculate the infiltration rate.

$$I = (KM) / (D^2 * t) \qquad (1)$$

where, K= Conversion factor 126,870 ($in^3 s$)/(lbs)
M = Mass of infiltrated water (lbs)
D = Inside diameter of infiltration ring(in)
t = Time to infiltrate water (sec)
I = Infiltration rate (inches/hr)

Figure 5: ASTM C1701 Standard Infiltration Test.

Compressive strength analysis of porous concrete was carried out by the ASTM C39 standard testing method as in Figure 6. Three cubes were cast for one test to get an average value. Curing was done for 7 days and 28 days respectively.

Figure 6: ASTM C39 Standard Compressive Strength Test.

150mm * 150mm * 150mm cubes were cast from porous concrete as indicated in Figure 7. Next, concrete was filled in the moulds in layers approximately 50mm thick. Then, each layer was compacted with not less than 35 strokes per layer using a tamping rod. After that, the load was applied gradually without shock and continuously at the rate of 140 kg/cm2/min, till the specimen failed. Finally, the maximum load was recorded at the failure moment.

Figure 7: Casted porous concrete cubes.

A slump test was carried out for all the mix designs to get an idea of the workability of porous concrete. But, as in Figure 8, the slump was zero. This indicates that the porous concrete is not slump concrete. To get a slump value, admixtures should be added accordingly, or the mix design ratio should be changed.

Figure 8: No slump concretes.

4. Results and Discussion

After conducting mixed designs, the results were plotted, and analyses were done in different ways.

4.1 Impact of Compaction on Porous Concrete

In mix design 2, the main objective was to compare compacted porous concrete slab panels and non-compacted porous concrete slab panels. The compressive strength and infiltration rate of compacted and non-compacted porous concrete cubes were also compared, and results were as follows in Table 2.

Table 2: Compressive Strength of 7 Days and Infiltration Test Results for Mix Design 2

Compaction Method	**Compacted**	**Non-Compacted**
Average Compressive Strength Value after 7 days	14.36 MPa	4.19 MPa
Average Infiltration Rate	422.50 inches/hr	1057.58 inches/hr

As a result, non-compacted cubes did not achieve the targeted strength. So, slab panels should be cast as compacted porous concrete. When the compacted and non-compacted slab panels were subjected to infiltration tests, the results had a huge difference.

The infiltration rate of the non-compacted slab panel was very high. The reason may be due to high voids in non-compacted porous concrete slab panels. However, the targeted compressive strength was not achieved by that slab panel. Therefore, the non-compaction method was not considered for the experiments. Only compacted porous concrete slab panels were considered for other mix designs.

4.2 Impact of Aggregate Size

In the first 4 mix designs, we changed the gradation curves for coarse aggregates. No fine aggregates were used. Tabulation of the Infiltration rate with different 12.5 - 25 mm were shown below in Figure 9.

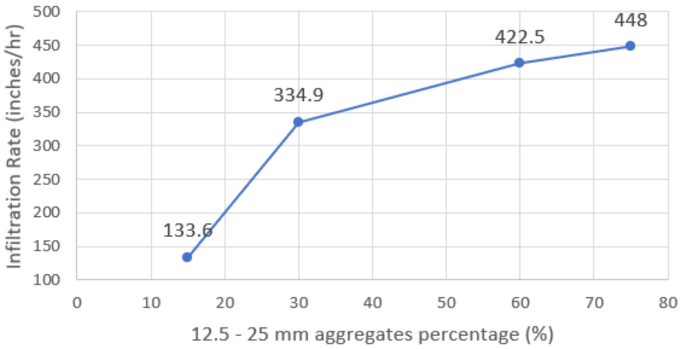

Figure 9: Infiltration rates for Mix Designs 1-4.

When increasing the 12.5 - 25 mm aggregate percentage, the infiltration rate increased. The Compressive Strength of casted cubes after 7 days were as below in Figure 10. It can be seen that when the 12.5 - 25 mm coarse aggregate particle sizes are increasing, the compressive strength will be lesser.

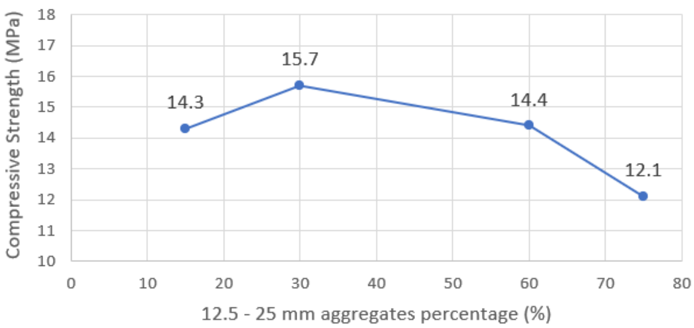

Figure 10: Compressive Strength after 7 days for Mix Designs 1-4.

4.3 Impact of Adding Fine Aggregates

For mix designs 5 - 7 fine aggregates were added in different proportions. The sand was used as fine aggregates. Fine aggregate percentages were changed to 10%, 20% and 30%. For coarse aggregates, the same gradation curve was used as in Figure 11 for mix designs 5-7.

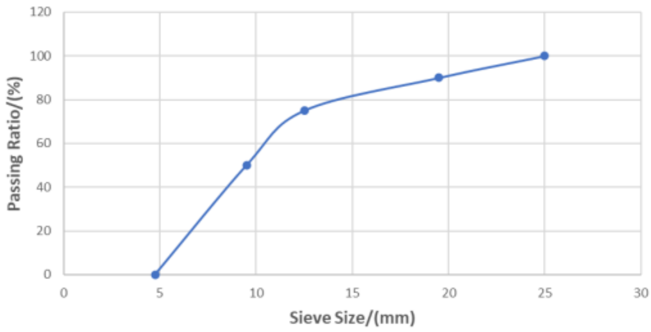

Figure 11: Coarse aggregates gradation curve for Mix Designs 5-7.

The infiltration rate values decreased when the fine aggregate percentages increased as in Figure 12. This can occur mainly due to the voids being filled by the fine particles. So, porosity will be decreased. However, the compressive strength values were increased with the higher fine aggregate percentages.

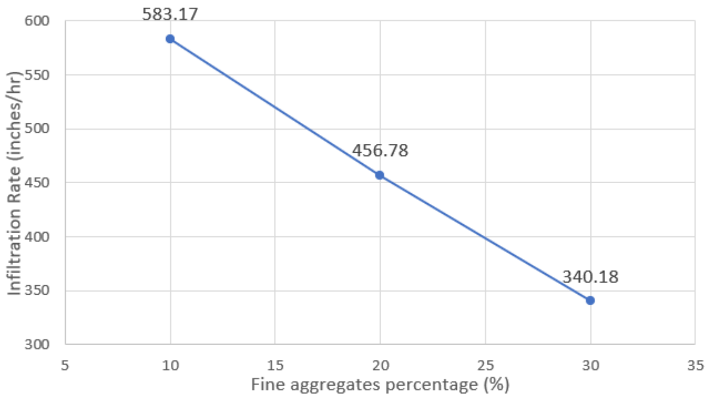

Figure 12: Infiltration rate values for Mix Designs 5-7.

4.4 Performance of Porous Concrete from Construction Waste

For mix design 8, we used construction wastes instead of normal coarse aggregates. Construction wastes such as concrete, bricks, wood etc. were collected from a construction site. The average compressive strength value was 16.28 MPa after 28 days. The infiltration rate value was 1413.06 inches/hr on average.

4.5 Discussion

The major objective of this research was to use recycled waste aggregates to construct a durable sustainable drainage system. The final mix design ratio can be used as 1: 4.3: 0.3 for porous concrete manufacturing. The gradation curves of coarse aggregates can be changed by following the eight mixed design patterns. Moreover, adding fine aggregates is an option. A fine aggregate layer can be added, and it will reduce the infiltration rate of porous concrete. This will increase the compressive strength and can be used for pavements as well.

To replicate urban runoff or flooding conditions for any catchment region using the 2d Hec-Ras software, by applying experimental infiltration values. It can be done for an ideal space or any actual location, such as a parking lot, a housing complex, a footpath etc. Normal concrete should be replaced with porous concrete. In urban locations, overflowing drains or runoff can be reduced by correctly constructed drain systems or pavements with porous concrete. It may be affordable and sustainable to produce porous concrete from construction waste. These porous slab panels can help prevent urban flooding by being used in parking lots and walkways. The infiltrated water can be collected separately from perforated pipes or any other appropriate method. Adding a fine particle layer to the top surface of porous pavements can be used in heavily flooded urban areas to strengthen the road pavement.

5. Conclusion

After conducting many lab experiments for different porous concrete mix designs, the following were the main conclusions.

- The compaction increased the compressive strength of porous concrete. Average compressive strength values after 7 days for compacted cubes was 14.36 MPa and for non-compacted cubes was 4.19 MPa.
- To increase the infiltration rate of slab panels, coarse aggregate particle sizes should be increased. When 12.5 – 25mm coarse aggregate percentage increased from 15% to 75%, the infiltration rates increased gradually from 133.6 inches/hr to 448 inches/hr. However, the 7-day compressive strength decreased from 14.3 MPa to 12.1 MPa.
- When fine aggregates were introduced from 10% to 30%, the compressive strength increased from 16.5 MPa to 18.21 MPa and the infiltration rates decreased from 600 inches/hr to 320 inches/hr. On average, 20% of fine aggregates can be used to achieve a strength of more than 17 MPa and it will have an infiltration rate of more than 450 inches/hr.
- Construction waste can be used to manufacture porous concrete. The average compressive strength value was 16.28 MPa after 28 days and the infiltration rate value was more than 1400 inches/hr on average, which shows its potential to be used in urban flooding areas.

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INVESTIGATION OF PROPERTIES OF CONCRETE RELEVANT TO EARLY-AGE THERMAL CRACKING

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Abstract: The occurrence of early-age thermal cracking presents a significant challenge to the durability and safety of concrete structures, leading to heightened maintenance and repair expenditures. Various factors influence the occurrence of early-age thermal cracks in concrete. Among the Temperature difference of members, the Coefficient of Thermal Expansion of concrete (CTE - α_c), the Coefficient for the effect of stress relaxation due to creep under sustained loading (K_1), Restraint Condition. The tensile stress capacity of the concrete at that age is important. This study primarily focuses on the CTE of concrete during early ages and K_1. Charnockite gneiss stands as the most commonly used aggregate in Sri Lanka's construction industry. However, the design codes and guidelines do not provide the α_c value for the concrete produced using this aggregate. Additionally, the study delves into investigating the basis and value of the coefficient (K_1) responsible for stress relaxation due to creep under sustained loading. To address this issue, an innovative test setup utilizing available techniques was developed to accurately measure α_c values. The obtained results indicate that the CTE of the concrete samples exceeds the conventional value used in Sri Lanka (10 με/C), highlighting an increased risk of cracking due to temperature changes. Furthermore, find the K_1 factor is not a constant value for every situation to estimate the restrain strain by the equation. The K_1 factor's variability necessitates the development of a sophisticated finite element model to estimate its impact accurately. This model takes into account diverse factors affecting early-age concrete behavior and offers a robust method for predicting stress relaxation. By providing insights into thermal characteristics and addressing a critical issue in construction, this research contributes to more informed design and construction practices, ultimately enhancing the sustainability and safety of built environments.

Keywords: Concrete Early-Age Thermal Cracking; Coefficient of Thermal Expansion (CTE) of Concrete; Charnockite Gneiss; Coefficient for the effect of stress relaxation due to creep under sustained loading; Creep Ratio

1. Introduction

Concrete is the most widely used construction material in the world, playing a crucial role in the development of infrastructure such as buildings, bridges, and roads. However, one of the challenges faced by concrete structures is the occurrence of thermal cracking during their early age. Early-age thermal cracking can compromise the durability and safety of concrete, leading to significant maintenance and repair costs. The early age of concrete is a critical period where various properties undergo rapid changes due to the exothermic nature of cement hydration. As cement hydrates, it releases heat, causing a rise in temperature within the concrete. Subsequently, the rate of heat loss to the environment causes the concrete to cool down, resulting in the contraction of hardened material and the development of thermal stresses. If the concrete is completely unrestrained and insulated, it undergoes free expansion and contraction without inducing harmful stress.

However, in real-life scenarios, internal and external restraints generate stress that can exceed the tensile strength of concrete, leading to cracking. To prevent such cracking and ensure the durability and safety of concrete structures, it is crucial to accurately determine the early-age thermal properties of the concrete. Two key factors that play a major role in this regard are the Coefficient of Thermal Expansion and the creep coefficient (K_1). The Coefficient of Thermal Expansion quantifies how much concrete expands or contracts with temperature changes, allowing engineers to predict and mitigate the effects of temperature differentials. The creep coefficient accounts for concrete's long-term deformation and stress relaxation under sustained loading, providing insights into the material's behavior over time. In the case of Sri Lanka, there is a lack of relevant information regarding the properties of local materials, such as the Charnockite coarse aggregate which is the most used coarse aggregate in Sri Lanka (Arulmoly, Konthesingha, Nanayakkara, & Premasiri, 2022).

In the industry, codes, and research publications, particularly the Euro and BS codes used in design works in Sri Lanka, provide material properties. However, there is no CTE value specified for concrete made from Charnockite Gneiss. As a result, a default value of 10 microstrains per Celsius is recommended. It is the value of concrete made of granite. But knowing this value properly is important in various aspects. (CTE -10 x 10^{-6} /°C, K_1= 0.65) (Bamforth, 2007) The accuracy and background of constant values used in the industry, such as the stress relaxation factor, require further investigation. Therefore, this research aims to evaluate the concrete Coefficient of Thermal Expansion at an early age, specifically considering local materials (Charnockite Gneiss) used in Sri Lanka. The study will also investigate the basis and value for the creep coefficient, considering the effect of stress relaxation due to creep under sustained loading. By obtaining accurate and reliable values for these thermal properties, the research aims to provide valuable information for the design and construction of concrete structures, ensuring the prevention of early-age thermal cracking and improving overall durability and safety.

2. Methodology

2.1 Coefficient of thermal expansion

To precisely measure the Coefficient of Thermal Expansion value, a new test setup was developed.

2.1.1 Materials and Mixture Proportions

To validate the accuracy and relevance of the new test method, a steel bar (length 385 mm and diameter 42 mm) with a known CTE value ($11.7 \times 10^{-6}\,^{\circ}C^{-1}$ to $12 \times 10^{-6}\,^{\circ}C^{-1}$) was used as a reference material.

To determine α_c, a 395 mm long, 90 mm diameter concrete specimen was cast using Charnockite gneiss coarse aggregates. These aggregates had a maximum size of 20 mm, because of the small size of the concrete test specimen. The mold was created using a 90 mm PVC tube, and three holes were drilled along the tube to accommodate thermocouples. W/C is 0.47. The sample tested was of C30 grade, and the mix proportion is outlined below.

Table 1: Proportions of concrete mixture

Constituent	Quantity
Cement (O.P.C) kg/m^3	380
Water kg/m^3	176
Fine Aggregates(River sand) kg/m^3	857
Coarse Aggregates. kg/m^3 (Charnockite gneiss)	1007
Superplasticizer l/m^3	3.99

To monitor temperature variations during the test within the concrete sample, three thermocouples were strategically installed during the casting. These thermocouples are consistently placed at a depth of 45 mm from the specimen's surface. The first one is positioned 50 mm from the left end, the second at 197 mm, and the third at 345 mm from the left end of the specimen.
Furthermore, to determine the CTE of the Charnockite gneiss aggregate which is commonly used in Sri Lanka as a coarse aggregate, a rock sample (length 395 mm and diameter 55 mm) taken from the bedrock was utilized. The rock sample represented the aggregate component of the concrete mixture. By measuring the coefficient of thermal expansion of the rock sample, the researchers could gain insights into the CTE characteristics of the aggregate used in the concrete.

2.1.2 Test setup

A test similar to the methodologies outlined in AASHTO T336 (Transportation, 2023) and Tex-428-A (DIVISION, 2023)was conducted to measure the coefficient of thermal expansion. However, there were a few notable changes in the setup. Instead of utilizing a single Linear Variable Differential Transducer (LVDT), two laser transducers were employed to measure the change in length of the sample at both ends when subjected to temperature changes. Additionally, rather than constraining elongation in a single direction with the sample positioned vertically, here, the sample was placed horizontally on the support frame, allowing for changes in length in both directions. The concrete specimen was positioned on the support frame in a way that prevented any disturbance to its length changes caused by temperature variations and ensured that it remained stationary, unaffected by any other external factors. The test was further improved by adopting a different approach to temperature measurement. Unlike the AASHTO or TEXA methods, embedded thermocouples were used to obtain an average reading of the concrete temperature. During the placement of the laser and the sample, certain limitations were considered. The surface where the two laser beams made contact had to be smooth and even. Ensuring that the laser beam was horizontal concerning the sample was crucial to prevent shifts in the measuring point as the concrete sample changed length.

In this setup, the IL-065 model sensor head and the IL-1000 model Amplifier unit were practically employed. The sensor head maintained an effective distance of 65 mm from the laser head to the sample, offering a repeatability of 2 micrometers in measurements. Subsequently, the concrete sample, embedded with these thermocouples, was submerged in a water bath and meticulously monitored using high-precision laser transducers to measure linear deformation in response to temperature changes. This data helped determine the material's response to temperature variations.

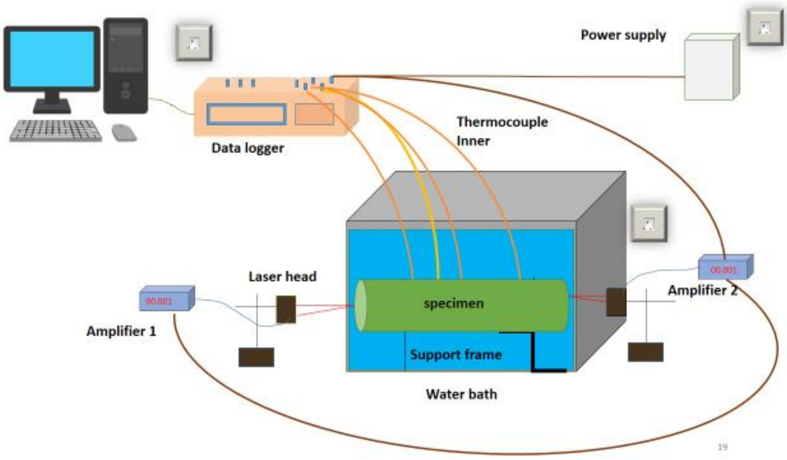

Figure 1: The schematic description of the test setup.

2.1.3 Test Procedure

The test procedure involves evaluating the thermal expansion characteristics of a cylindrical test specimen made from C30 concrete. To begin, a test specimen is prepared, and three thermocouple wires are inserted into it for temperature monitoring. This specimen is then conditioned in saturated limewater for a period of 48 hours. Then Surface moisture is carefully removed, and the specimen's initial length at room temperature is measured and recorded. Subsequently, the prepared specimen is placed within a water bath on a support frame. To measure deformation, two laser transducers are set up and installed on the specimen. Additionally, a thermocouple wire is inserted into the water bath to continuously measure the water temperature. Both the thermocouple wires and laser transducers are connected to a data logger for real-time data acquisition. Throughout the testing process, the values provided by the laser transducers and the water temperature from the thermocouple wire are monitored. As the temperature changes, the specimen undergoes expansion or contraction, which is recorded by the laser transducers. These measurements are collected and analyzed to create a graphical representation of temperature versus specimen elongation, allowing for the calculation of the coefficient of thermal expansion.

2.2 Coefficient of Stress Relaxation Due to Creep Under Sustained Loading

The behavior of concrete under sustained loading and the potential for cracking due to creep are evaluated using two measures: creep coefficient and creep ratio. The creep coefficient is calculated as the ratio of creep strain to the elastic strain at a given time. It is a measure of the extent to which a material deforms over time under sustained loading. On the other hand, the creep ratio is the ratio of tensile strain due to creep to the free shrinkage strain. (Farrington, Burns, & Carrasquillo). The creep/shrinkage ratio is a useful measure because it indicates how much the development of tensile strain in the restrained concrete is reduced, and thus provides insight into the degree of stress relaxation that has occurred. (Altoubat & Lange, 2001). This concept can be mathematically represented by the following equation, which I have developed based on the available research findings.

$$K_1 = 1 - \text{Creep ratio} \qquad (1)$$

$$K_1 = 1 - \frac{creep\ strain}{shrinkage\ strain}$$

$$K_1 = \frac{shrinkage\ strain - creep\ strain}{shrinkage\ strain}$$

$$K_1 = \frac{effective\ strain}{shrinkage\ strain}$$

This can be illustrated below.

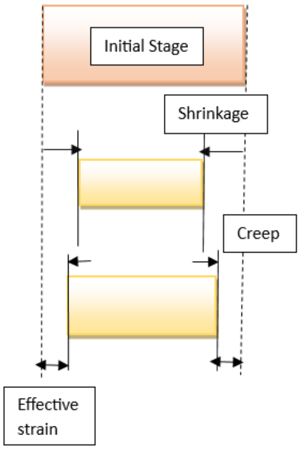

Figure 2: Effect on Stress Relaxation Due to Creep Under Sustained Loading.

$$\varepsilon_T = R \times K_1 \times \Delta T \times \alpha_c \qquad (2)$$

Equation (2) calculates the strain in concrete due to temperature variation under restrained conditions. It considers the limited deformation of concrete caused by restraint, represented by the R-value. The K_1 value represents the effect of creep resulting from stress generated in concrete when a certain strain is applied. It essentially quantifies the reduction in the initial strain caused by the creep phenomenon. By multiplying the initial strain ($R \times \Delta T \times \alpha_c$) of concrete by K_1, we can calculate the specimen's final strain due to the early age thermal effect.

By incorporating these factors, the equation provides a comprehensive estimation of effective strain in concrete when exposed to temperature changes. This approach considers the combined effects of temperature, restraint, stress, and creep on concrete deformation.

Creep and shrinkage have an impact on the early-age strain of concrete, with K_1 serving as a representative value for this effect. Nonetheless, a more comprehensive study is required to thoroughly examine K_1's influence on early-age thermal cracking and evaluate the reliability of using the value of 0.65.

3. Results and Discussions

3.1 Coefficient of Thermal Expansion

3.1.1 Validation of the test - measure steel bar CTE

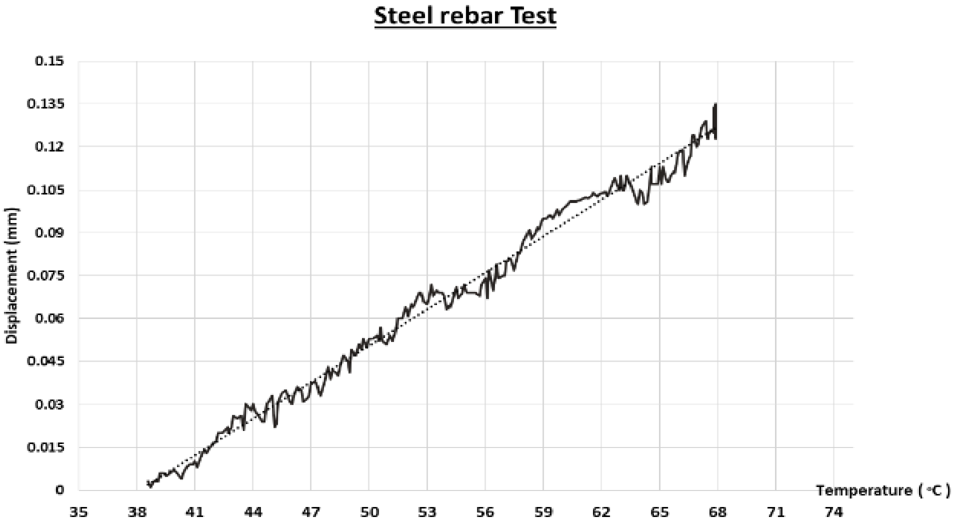

Figure 3: Deformation Vs. Temperature of the Steel bar.

$$CTE = \frac{\blacktriangle e}{\blacktriangle \theta \times L} \qquad (3)$$

L – Length of the specimen (At initial temperature)

$\blacktriangle e$ – Total Length change of Specimen

$\blacktriangle \theta$ – Temperatureifference

Length of the specimen (385 mm)
CTE= **12.06** με °C^{-1}

Based on the obtained results, Figure 3 was created. The CTE value calculated for the steel rebar closely matches the range of values previously reported in existing research papers(11.7 × 10^{-6} °C^{-1} to 12 × 10^{-6} °C^{-1}) (Boyes, 2010). Consequently, this test method's precision is affirmed, rendering it suitable for the subsequent phases of the research study.

3.1.2 Measure Concrete CTE

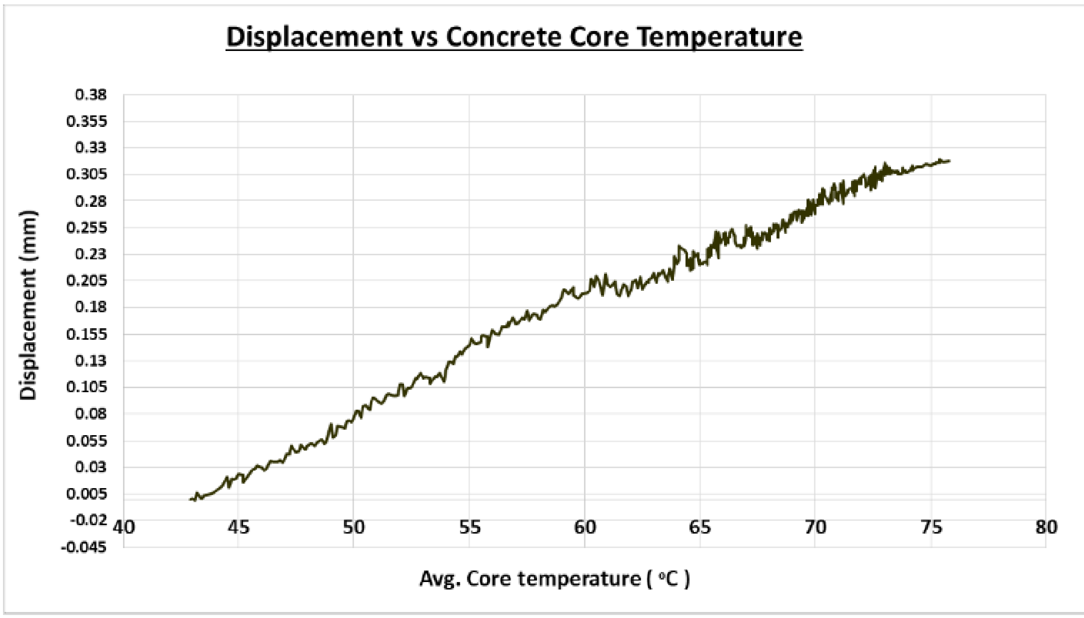

Figure 4: Deformation Vs. Temperature - Concrete sample.

3.1.3 Measure rock sample CTE

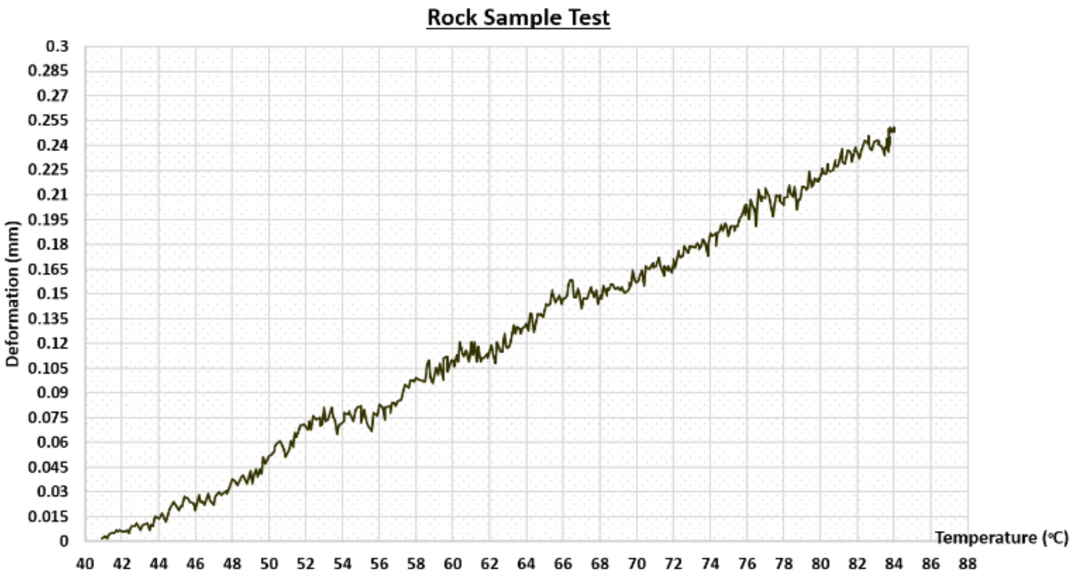

Figure 5: Deformation Vs. Temperature - Rock sample test.

To obtain the ▲e value, the sample temperature was kept constant for a few minutes until a stable reading was achieved. The temperature (▲θ) difference was calculated by subtracting the initial measured temperature of the specimen from the last stable temperature.

These graphs are created using the changes in total length and temperature of the concrete specimen as the temperature increases. During the test, the alterations in the length of each face are measured and combined to determine the overall length change. The water bath heats the water, and a fan, when activated and rotated, is employed to maintain a uniform temperature throughout the water bath by effectively stirring the water within it.

Table 2: CTE Calculation

Graph no	Specimen	Length of the specimen (mm)	CTE $\mu\varepsilon\ C^{-1}$
3	Steel	385	**12.06**
4	Concrete	395	**12.92**
5	Rock	395	**14.43**

3.1.4 Significance of the results

Using inappropriate values for the CTE can reduce the effectiveness of measures taken to mitigate early-age thermal cracking in concrete.

To prevent thermal and shrinkage cracks and ensure structural integrity, it is necessary to increase the reinforcement area by **29.2 %** compared to the previous calculation using an α_c value of **10×10^{-6} $\mu\varepsilon\ C^{-1}$** (same conditions). Failure to do so can result in cracking, compromising the safety and structural integrity of the construction.

This further reduces the maximum temperature difference that can exist without cracking at an early age of concrete.

Limits of ΔT_{max}

$$\Delta T_{max} = \frac{\varepsilon_{ctu}}{R \times K_1 \times \alpha_c} \qquad (4)$$

(ε_{ctu}) - Tensile strain capacity under sustained loading

Table 3: Limits of ΔT max

Concrete grade	C25/30	C30/37	C35/45	C40/50	C50/60	C55/67	C60/75
Tensile strain capacity under sustained loading at an early age (3 days) (Bamforth, 2007)	70	75	81	85	92	98	104
ΔT_{max} (CTE- 10×10^{-6} C^{-1}) (Bamforth, 2007)	26	28	30	31	34	36	38
ΔT_{max} (CTE- $12.92 \times 10^{-6} C^{-1}$)	20	22	24	25	27	28.5	30.5

Increased CTE in concrete may impact fire propagation in buildings, causing greater dimensional changes and thermal stresses. This could lead to cracking, spelling, and compromised structural integrity, potentially accelerating the spread of fire and endangering occupants' safety. Considering that a substantial number of Sri Lankan buildings are constructed using this concrete, a better understanding of these parameters becomes exceptionally valuable in ensuring the safety and resilience of such structures.

3.2 Coefficient of stress relaxation due to creep under sustained loading

The research conducted by (Altoubat & Lange, 2001) reveals several important findings regarding the effect of creep/shrinkage on the early-age strain of concrete:

1. The creep/shrinkage ratio at the time of cracking for restrained concrete is approximately 0.5, regardless of the water-cement ratio (w/c) of the mixture. This indicates that tensile creep relaxes shrinkage stresses by at least 50% for normal and high-performance concrete.

2. The creep/shrinkage ratio initially has a high value for the first two days and then decreases over time to approach a stable value.

   This suggests that creep and shrinkage behavior in concrete changes over time, including the early age. Notably, the K_1 value, which represents these effects, varies in the early days of concrete, indicating it's a time-dependent factor rather than a constant. Altoubat's study proposed a value of 0.5, which deviates from the commonly used 0.65, emphasizing the need for a more comprehensive understanding of these dynamic properties
   According to much modern research, it is revealed that several factors affect the creep/shrinkage ratio. That is, it can show different values under conditions varying. (Farrington, Burns, & Carrasquillo)

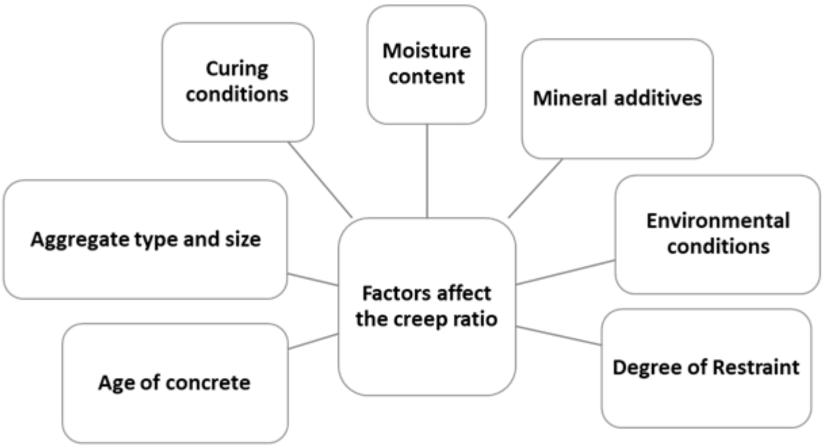

Figure 6: Factors that affect the creep ratio.

Another study (Tao & Weizu, 2006) investigated the effect of the degree of restraint conditions on creep behavior in high-strength concrete at early ages. They observed variations in the creep/shrinkage ratio based on the degree of restraint, with different levels of creep and shrinkage for different conditions. They also found that mineral additives in cement, such as fly ash and silica fume, have a significant influence on creep and relaxation properties at early ages.

Table 4: The effect of the restraint degree on creep behavior

Degree of restraint conditions	**Creep/shrinkage ratio**	**K_1**
100	0.62	0.38
75	0.5	0.5
50	0.45	0.55

Table 5: Mineral additives' effect on K_1

Type of concrete	**Creep/shrinkage ratio**	**K_1**
O.P.C	0.45	0.55
S.F (6% replacement of O.P.C)	0.67	0.33

F.A (30% replacement of O.P.C)	0.3	0.7

Here are some values for creep ratio and K_1 that have been introduced in various research studies, indicating their dependence on different conditions:

Table 6: Early research findings

<table>
<tr><th>Research</th><th colspan="4">Creep coefficient (C.C) and Creep shrinkage ratio (C.R)</th><th></th></tr>
<tr><td>Bamforth (1985)</td><td colspan="3">0.35</td><td></td><td></td></tr>
<tr><td>Vitherana et al (1995)</td><td colspan="3">0.35</td><td></td><td></td></tr>
<tr><td rowspan="4">Lang, Salah A. Altoubat and David A., (2001)</td><td colspan="3">1</td><td rowspan="2">C.C</td><td>0.5 W/C ratio</td></tr>
<tr><td colspan="3">1.5</td><td>0.4 W/C ratio</td></tr>
<tr><td colspan="3">0.5</td><td rowspan="2">C.R</td><td>0.5 W/C ratio</td></tr>
<tr><td colspan="3">0.6</td><td>0.4 W/C ratio</td></tr>
<tr><td rowspan="4">Zhang et al. (2017)</td><td></td><td>S. A</td><td>I.T</td><td rowspan="4">C.R</td><td rowspan="4">0.35 W/B ratio
High-performance concrete</td></tr>
<tr><td>F. A</td><td>0.22</td><td>0.6</td></tr>
<tr><td>O.P.C</td><td>0.41</td><td>0.51</td></tr>
<tr><td>S. F</td><td>0.61</td><td>0.4</td></tr>
</table>

S.F - Silica fume concrete, F.A- Fly ash concrete, O.P.C - Plain concrete,
I.T- Isothermal, S.A-Semi-adiabatic conditions.

In modern construction, blended cement is preferred over pure OPC. Our results reveal that the common K_1 value of 0.65 can either underestimate or overestimate real effects. The degree of restraint condition is also a major factor. In addition, Figure 6 represents other factors that affect the creep coefficient ratio. The value of K_1 at 0.65 was initially proposed in 1985. In light of contemporary research, the reliability and constancy of this value come into question. Such discrepancies can engender various issues. Underestimating K_1 leads to inadequate reinforcement for thermal crack prevention and the potential propagation of cracks in the concrete. Conversely, overestimating K_1 can result in uneconomical designs. Both scenarios have the potential to impact the safety, structural integrity, and overall economic viability of a structure. These findings emphasize that the creep/shrinkage ratio is variable, influenced by factors like restraint degree and mineral additives, significantly affecting the coefficient (K_1). Table 5 shows the value of K_1 varies between 0.39 and 0.78 based on the results under different conditions. Hence, it's crucial to consider these factors when evaluating concrete creep and shrinkage behavior.

4. Conclusions and Recommendations

In conclusion, the conducted tests have provided valuable insights into the coefficient of thermal expansion of different materials. The newly validated test method accurately measured the CTE of a steel bar, validating its accuracy. Concrete samples using local aggregates (Charnockite gneiss) demonstrated a CTE value of 12.92 με/C, indicating the specific thermal expansion behavior of the concrete with the given aggregate type. Additionally, the Charnockite gneiss rock sample, which is highly used as a coarse aggregate in construction in Sri Lanka exhibited a CTE value of 14.43 με/C. These findings contribute to our understanding of the thermal expansion characteristics of these materials, which is essential for various applications and design considerations in construction and engineering.

The limited test results indicate that the CTE of the concrete sample exceeds the typical value used in Sri Lanka (10 $\mu\varepsilon/^{\circ}C$), suggesting a higher risk of cracking due to temperature changes. To mitigate this risk, further tests, including physical experiments or finite element modeling, should be conducted to validate these findings. To get accurate CTE value for concrete a large sample of tests should be done by changing the mix proportions of the concrete. Then get a characteristic value to CTE Such validation is crucial for addressing potential issues and ensuring the safe construction of concrete structures. According to the above information, it is not appropriate to present a specific constant value for the coefficient of stress relaxation under sustained loading (K_1). This value varies depending on factors such as the type of mineral additives and the degree of restraint. Therefore, this value should be considered as a function of these factors and appropriate values should be recommended for the respective conditions. It is recommended to develop a finite element model to estimate the K_1 coefficient of concrete. This model should incorporate factors such as degree of restraint, mineral additives, drying conditions, and other relevant parameters. To ensure its accuracy and reliability, the model should be validated using experimental data obtained from various conditions. Additionally, conducting studies to investigate the individual effects of these factors on early-age concrete behavior is suggested. These studies aim to quantify the influence of each factor and develop equations to accurately quantify their effects. By combining these approaches, a better understanding of early-age concrete behavior can be achieved, leading to more effective strategies for designing and constructing concrete structures.

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OPTIMIZING SOLAR ENERGY HARVESTING THROUGH AI-BASED DUAL-AXIS SOLAR TRACKING SYSTEM WITH REMOTE MONITORING

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Abstract: The solar harvesting system is popular these days since it produces clean and effective energy. The system's efficiency can be maximized by positioning the solar panels at the exact angle and direction dictated by the motion of the sun. This research project uses a solar tracking system that follows the sun along both its horizontal and vertical axes. The main goal is to develop a clever tracking algorithm that precisely lines up the solar panel with the position of the sun to maximize energy production from solar radiation. To determine the effectiveness of the data-driven dual-axis solar tracking system, extensive testing and assessment are carried out. In comparison to fixed solar installations, the research intends to quantify the increase in energy output made possible by careful solar panel orientation. The results of this study offer important new perspectives on the conception and application of clever solar tracking systems based on four LDRs, a Bluetooth module, a current sensor, and a voltage sensor. A simple and accessible method for raising awareness of sustainable renewable energy practices and improving the efficiency of solar energy harvesting is provided by the incorporation of MIT App Inventor for remote monitoring. This project aims to significantly advance the design and application of intelligent solar tracking devices by utilizing advanced data analytics and real-time remote monitoring. The data-driven methodology used in this study offers encouraging potential for increasing the usage of solar energy and hastening the deployment of clean and effective solar power technology within the field of artificial intelligence, the Support Vector Regression (SVR) method. This unity of purpose emphasizes SVR's ability to correctly forecast angles for efficient energy harvesting. It is important to emphasize, however, that the successful deployment of SVR involves painstaking data preprocessing, careful parameter adjustment, and stringent validation processes.

Keywords: Solar tracking system; Data-driven optimization; LDRs (Light Dependent Resistors); Voltage & Current sensor; Remote monitoring app; Support Vector Regression (SVR)

1. Introduction

The extensive use of solar energy as a clean and sustainable substitute for traditional fossil fuels is a result of the growing need for renewable energy sources. However, maximizing the use of this rich resource still faces significant challenges related to solar energy harvesting efficiency. By continuously aligning solar panels to track the sun's movement throughout the day, dual-axis solar tracking systems have become an innovative way to maximize solar energy generation. Light Dependent Resistors (LDRs), a current sensor, and a voltage sensor are used in this study to create a data-driven dual-axis solar tracking system. The main objective is to develop an intelligent tracking system that can dynamically change the angles of the solar panels to exactly coincide with the sun's shifting location. Real-time data is gathered and analyzed to determine the best orientation of the solar panels, ensuring they get the most solar radiation. This is done by integrating LDRs into the system to detect ambient light intensity and incorporating a current sensor, and a voltage sensor to monitor solar panel output. The selection of the most appropriate artificial intelligence algorithm for the data-driven dual-axis solar tracking system is critical for effectively predicting solar panel orientations based on the acquired data. Support Vector Regression (SVR) appears as a strong candidate in this situation. SVR is a specific machine learning method that is particularly successful when dealing with continuous numerical predictions.

The creation of a user-friendly remote monitoring application using MIT App Inventor is a crucial component of this research, in addition to the hardware components. Users of this remote monitoring application have immediate access to vital information and performance parameters, the amount of energy produced, and the effectiveness of the system. With that capability at their disposal, users may make well-informed decisions to maximize energy output and enhance the solar tracking system's overall performance. Extensive testing and evaluation will be done throughout the study process to accurately compare the data-driven dual-axis solar tracking system to fixed solar installations. A greener and more energy-efficient future will be encouraged by the findings, which will be crucial in encouraging sustainable renewable energy practices and speeding up the adoption of clean and efficient solar power technologies.

2. Literature Review

Due to its availability, sustainability, and low environmental effect, solar energy is becoming more and more significant as a practical renewable energy source (Abid, 2012) (V.Brahmeswara Rao1, 2017). Solar tracking systems have received a lot of attention as an efficient way to maximize energy production by keeping optimal solar panel orientation throughout the day, which will increase the effectiveness of solar energy harvesting (V.Brahmeswara Rao1, 2017) (Al-Waily, 2014).

The integration of Light Dependent Resistors (LDRs) with a current sensor, and a voltage sensor is the topic of this literature review, which examines major discoveries and advancements in the field of data-driven dual-axis solar tracking systems. The benefits of dual-axis solar tracking systems over single-axis or fixed installations have been emphasized in several studies (V.Brahmeswara Rao1, 2017). According to (V.Brahmeswara Rao1, 2017) dual-axis tracking can boost energy output by up to 40% in comparison to fixed systems. Traditional dual-axis tracking systems, (Poudel, MAR 2021) (Emmanuel Karabo Mpodi*, 2019)on the other hand, frequently have expensive installation and maintenance costs, which restricts their general usage (Al-Waily, 2014) (Malik I. Al-Amayreh a, 2022). To overcome these difficulties, recent research has looked into the application of data-driven algorithms in solar tracking systems (Eric Tutu Tchao a b, 2022) (Nadia AL-Rousan a, 2020). For the tracking system to assess ambient light intensity, LDRs have been used for real-time determination of the sun's location (Vibha PatroCh, 2018). The work demonstrated the potential for accurate sun monitoring with less expensive and complicated technology (Chaowanan Jamroen a b, 2020) (P. Muthukumar a, 2023).

Additionally, a current sensor and a voltage sensor have been added to track the solar panels' production. The device may continuously modify the panel angles for optimum energy production by gathering real-time data on solar panel performance (Alessandro N. Vargas a, 2022) (M.H.M. Sidek a, 2017). Additionally, it has become clear that data logging and analytics are essential elements of data-driven solar tracking systems. Used data recording to track environmental factors, energy production, and solar panel orientations (Alessandro N. Vargas a, 2022) (Chaowanan Jamroen a b, 2021). It was possible to gain insights into prospects for energy optimization and system performance through the examination of the acquired data (Masoumeh Abdollahpour a, 2018) (Chien-Hsing Wu a, 2022).

The MIT App Inventor integration of a user-friendly remote monitoring application has been investigated to improve the usability and accessibility of solar tracking systems. Who created a smartphone app for remote monitoring and allowed users to view real-time data and remotely manage the solar tracker, which is built upon in this study (Chaowanan Jamroen a b, 2020) (John, 2020) (Khanam, et al., 2022).

3. Methodology

a. Overall Architecture

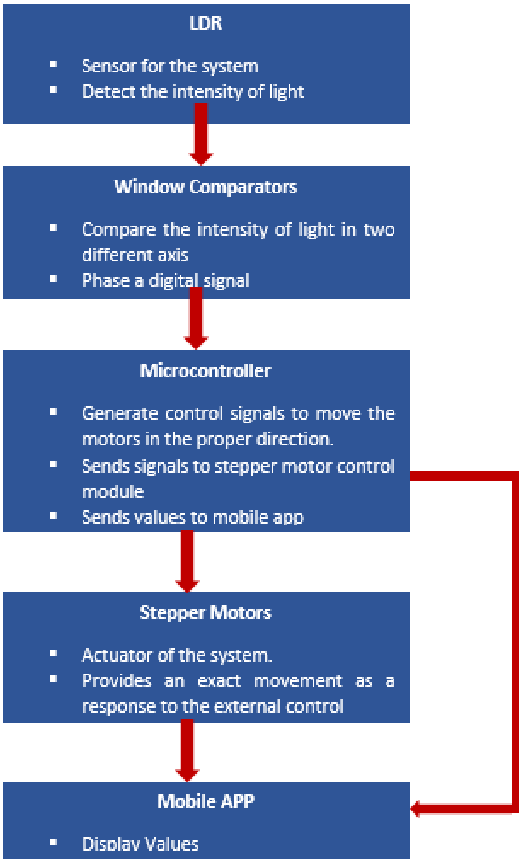


Figure 01. Overall Diagram of the Approach.

Figure 1. Shows the overall architecture of the system. It serves as a sort of road plan that outlines how everything fits together. It has specialized sensors, such as current sensors and light-

dependent resistors (LDRs). These sensors capture crucial data on the brightness of the sun's rays and the amount of electricity the solar panels are producing. The Atmega 328p microcontroller, the brain of the computer, receives all this data. Based on the information it receives, this brain comes to wise conclusions. The solar panels are also moved around by unique motors known as stepper motors. The microprocessor instructs them on how to spin, and as a result, the panels are perfectly facing the sun. Additionally, employ the clever Support Vector Regression (SVR) technique to make educated guesses regarding the ideal panel angles. There is an app that anyone with a phone can use. This app, which was created with MIT App Inventor, allows one to view events as they are happening. Together, these factors make our solar tracking system incredibly smart and effective at capturing solar energy.

b. Real-World Implementation

To build proper linkages between components and maximize space usage, circuit design, and PCB layout are essential tasks. After the design was finished, the PCB fabrication was carried out. To achieve precise solar panel alignment and effective data collecting, the hardware development of the data-driven dual-axis solar tracking system comprises the careful selection and integration of important components. Figure 2 shows the assembly of the four LDRs and solar panels. The rotation is done in the axis as mentioned in Figure 2.

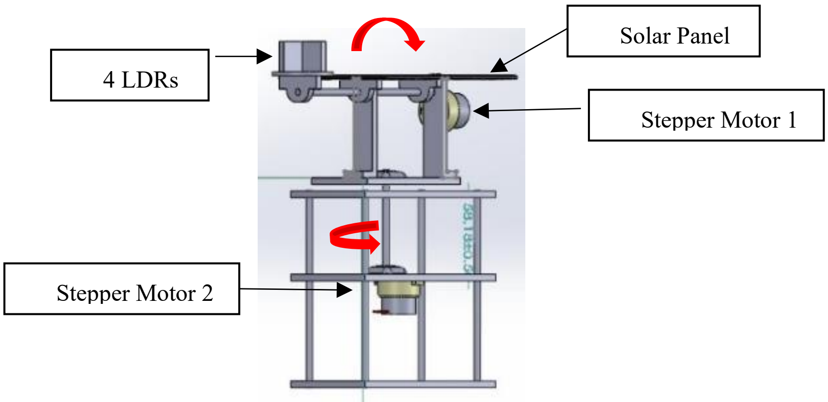


Figure 02. Design of the Solar Tracker using Solid-works.

After that, mechanical integration is done to align the stepper motor with the solar panel mounting structure, allowing for precise solar panel adjustments. The Atmega 328p microcontroller, current sensor, LDRs, stepper motor, voltage sensor, and enclosure box are only a few of the components that are chosen based on the requirements and compatibility of the system. To provide reliable and consistent power transmission to all components, an appropriate power supply is put into place. The assembled is shielded from the elements and potential physical harm by being placed inside a protective enclosure box. Figure 3. Shows the outcome of the system.

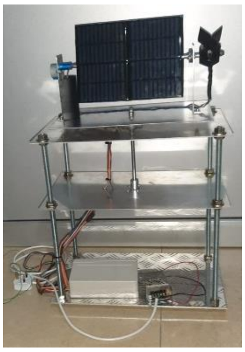


Figure 3. Final Outcome.

For the sun tracking test a small prototype was built and it is shown in Figure 4. To simulate the changing lighting conditions, this prototype consists Arduino board with Light Dependent Resistors (LDRs). The system is attached to a servo motor that simulates a solar panel's movement. The LDRs record variations in light intensity similar to the sun's path. The algorithms compute the sun position angles based on LDR readings and then control the stepper motor to move the ‘solar panel' in the desired location. Before moving on to actual solar panels, this small-scale prototype enables us to assess the viability and accuracy of our tracking system.

Figure 4. Prototype for Testing.

3.2.1 Adaptation of AI

Within the field of artificial intelligence, the Support Vector Regression (SVR) method appears as a highly viable contender for reliably forecasting solar panel orientations from gathered data. SVR excels at collecting complex, non-linear correlations between voltage and current measurements and the best angles for solar panels. This property is especially important in solar tracking systems because the interplay between these parameters is complex and non-linear.

The robustness of SVR in the face of noisy data is what distinguishes it for solar tracking applications. Given the real-world nature of data acquired from solar panels, which may be subject to changes caused by a variety of environmental conditions, SVR's ability to manage noise becomes critical. This unity of purpose emphasizes SVR's ability to correctly forecast angles for efficient energy harvesting and improve the efficiency of the smart solar tracking system when compared to other solar tracking systems. It is important to emphasize, however, that the successful deployment of SVR involves careful parameter adjustment. SVR's efficacy and smooth integration into the solar tracking system, offer improved angle prediction accuracy and increasing total energy harvesting efficiency.

3.3 Development of Monitoring Application

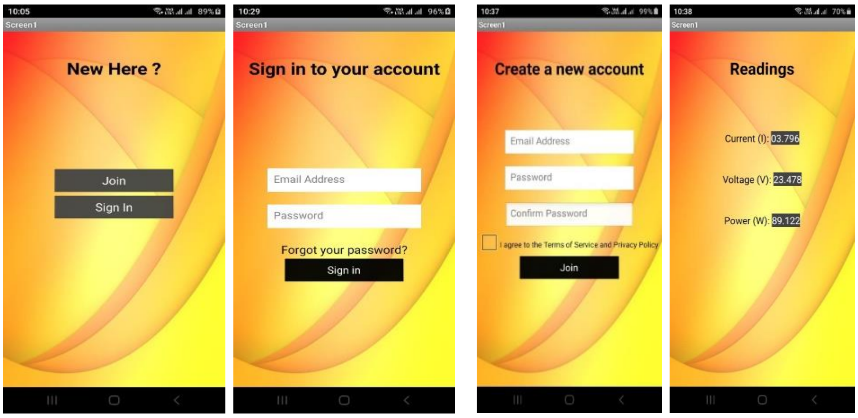


Figure 5: Pages of the Android App.

The many screens of the app are depicted in the above figure 5. Users can access their accounts through the login page, while new users can create accounts using the register page. The value display page highlights significant data, such as about energy production. The program features tabs for login in, joining up, and displaying significant info, to put it simply.

4. Results and Discussion

The solar tracking project can benefit from Support Vector Regression (SVR), a methodical procedure that increases angle forecast accuracy and overall system effectiveness. Using the Python sci-kit-learn module, the SVR model was created and assessed. The goal was to determine how well the model performed when compared to a fixed orientation scenario in terms of improving angle predictions.

The actual angles from the dataset were contrasted with the predicted solar panel angles from the SVR model. A thorough dataset including voltage, current, the time of day, and the appropriate solar panel orientations is first gathered. To train the SVR model and assess its effectiveness, this dataset is then divided into training and testing sets. The SVR model is then trained and assessed, with metrics like Mean Squared Error giving information about its correctness. The Mean Squared Error (MSE) was computed to objectively assess the performance of the model. The MSE calculates the average squared discrepancies between the expected and actual angles. The computed MSE in this experiment was 5.872, showing a level of agreement between the predicted angles and the measured angles. A lower MSE score suggests that the two sets of data are more closely aligned. The model constantly receives real-time voltage and current data for angle forecasts and is integrated into the solar tracking system's decision-making process. Ultimately, the improved model is put to use in a real-world environment, where it responds to shifting circumstances and adjusts the angles of solar panels for effective energy collecting. This all-encompassing strategy emphasizes how crucial careful data management, model training, and continuing system improvement are for attaining accurate and adaptive solar tracking.

$$\text{MSE} = \frac{\Sigma\ (\text{predicted value - actual value})^2}{\text{Total number of data points}} \quad (1)$$

The findings show that, when compared to actual angles, the SVR model effectively and somewhat accurately forecasts solar panel angles. As shown in Table 1, the model's predictions match the actual angles to some extent. The SVR model appears to adequately capture the underlying relationships between the voltage, current, and angle data based on the MSE value's comparatively low value of 5.872. This result highlights SVR's potential to increase the accuracy and output of solar tracking systems.

The SVR model performs admirably during periods of intense sunlight, which is consistent with the system's emphasis on maximizing panel angles for more energy absorption. In conclusion, the SVR model's initial attempt to predict solar panel orientations yields encouraging outcomes. These results create the groundwork for additional research and development, particularly through more complex implementations including extensive dataset gathering and extensive performance assessments.

Table 01: Angle Values

Predicted Angle	Actual Angle	MSE Value
73.771	75.171	5.872
76.71	81.571	6.21
72.895	71.987	5.405
79.312	80.652	6.98
75.993	77.389	5.902
77.041	75.912	5.613
80.645	81.786	6.487
82.218	82.991	6.924
83.106	83.427	7.042
79.885	80.125	6.312

Data on current and voltage were gathered periodically throughout the experiment, which was run from 7 am to 5 pm on consecutive days. The data gathered over several days provide important insights into the system's power requirements and energy consumption pattern throughout the course of various periods. It made it possible to analyze daily fluctuations in energy use, including times of high demand and low utilization. Using these readings as input, the power (P) was calculated using equation 01,

$$P = V \times I \qquad (2)$$

Where V stands for voltage and I for current. The instantaneous power consumption in watts (W) was calculated by multiplying the voltage and current readings for each time interval. The outcome is displayed in Graph 3 and it shows the maximum power output with the tracking of the solar system.

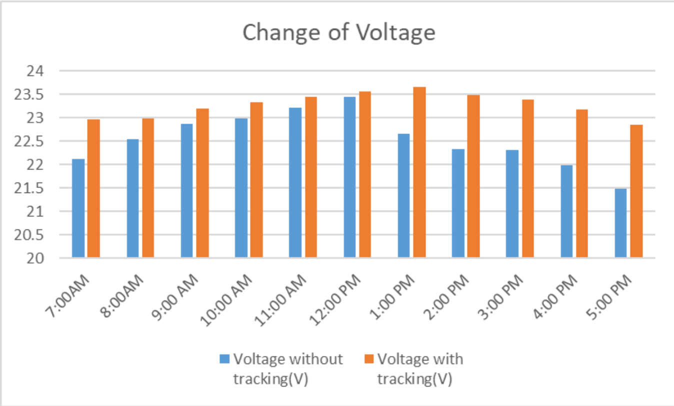
4.1 Comparison of Data Tables with Solar Tracking

i. Voltage:

Throughout the day, the "Voltage with Tracking" constantly registers increasing values. For example, at 10:00 a.m., the voltage is 23.335 V with tracking and 22.987 V without tracking (Table 2). This pattern holds throughout the day, with the gap expanding during peak sunshine hours (Graph 1).

Table 02: Output Voltage with and without tracking

Time	Voltage without tracking(V)	Voltage with tracking(V)
7:00AM	22.123	22.963
8:00AM	22.547	22.987
9:00 AM	22.874	23.198
10:00 AM	22.987	23.335
11:00 AM	23.211	23.435
12:00 PM	23.448	23.564
1:00 PM	22.654	23.659
2:00 PM	22.324	23.489
3:00 PM	22.311	23.388
4:00 PM	21.987	23.165
5:00 PM	21.487	22.845



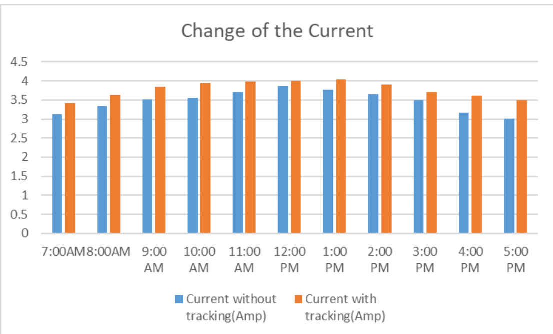
Graph 01: Change of the voltage.

ii. Current:

The "Current with Tracking" data outperforms the "Current without Tracking" data consistently (Table 3). For example, at 9:00 a.m., the current with tracking is 3.845 amps, but it is 3.512 amps without tracking. This pattern continues throughout the day, especially during the hours of direct sunshine (Graph 2).

Table 03: Output Current with and without tracking

Time	Current without tracking(Amp)	Current with tracking(Amp)
7:00AM	3.124	3.412
8:00AM	3.334	3.624
9:00 AM	3.512	3.845
10:00 AM	3.548	3.947
11:00 AM	3.714	3.975
12:00 PM	3.872	4.001
1:00 PM	3.769	4.048
2:00 PM	3.654	3.912
3:00 PM	3.489	3.701
4:00 PM	3.156	3.612
5:00 PM	3.014	3.502



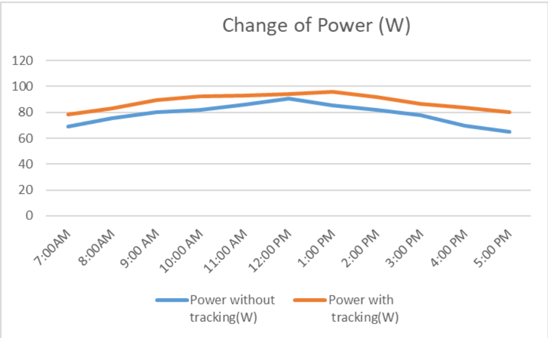
Graph 02: Change of the Current.

iii. Power:

With Tracking: "Power with Tracking" routinely produces greater values than "Power without Tracking."(Table 4). At 11:00 a.m., for example, the power output with tracking is 93.154 Watts, while it is 86.112 Watts without tracking. This discrepancy is maintained throughout the day (Graph 3).

Table 04: Power Output with and without tracking.

Time	Power without tracking(W)	Power with tracking(W)
7:00AM	69.112	78.349
8:00AM	75.171	83.304
9:00 AM	80.333	89.196
10:00 AM	81.557	92.103
11:00 AM	86.112	93.154
12:00 PM	90.791	94.279
1:00 PM	85.382	95.771
2:00 PM	81.571	91.888
3:00 PM	77.843	86.558
4:00 PM	69.391	83.671
5:00 PM	64.761	80.003



Graph 03: Change of power.

In summary, the "with tracking" scenario regularly beats the "without tracking" counterpart across all three data types—voltage, current, and power. This advantage is especially noticeable during peak sunshine hours when the solar tracking system's capacity to optimize panel angles by the sun's location greatly adds to increased energy generation. The discernible benefits shown by specific values highlight the real benefits of employing solar tracking equipment.

5. Conclusion & Future Works

The data-driven dual-axis solar tracking system with PCB designing, in conclusion, represents a substantial advancement in maximizing solar energy harvesting effectiveness as displayed in the results section. However, several possible areas for further study and development might improve the system's functionality and help a greater number of people adopt renewable energy sources. The system can be made to dynamically react to changing weather conditions and increase overall energy generation by investigating advanced control methods. Enhancing system resilience and efficiency through the integration of energy storage options and smart grid connectivity will enable excess energy to be stored and provided during times of low sunlight. Solar tracking systems can also become more available and appealing for a range of applications by looking into cost-effective substitutes for parts and materials. This approach gets closer to creating a greener and more sustainable energy future as keeps enhancing the system's outside toughness and dependability. Can improve the use of renewable energy sources and help create a cleaner, more sustainable world by looking at these prospective future research fields.

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KITHUL WOOD REBARS FOR LIGHTLY LOADED ONE-WAY SLABS

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Abstract: Steel serves as an optimal material for reinforcing concrete due to its desirable properties. However, it's a non-renewable material and incurs a high material cost as well as a high carbon footprint. Structural timber emerges as a renewable, sustainable, and cost-effective alternative. Some timber species such as Kithul wood (*Caryota Urens*) and bamboo *(Bambusa vulgaris*) exhibit commendable tension capacities due to their fibrous structure. Very low ductility and low fire endurance are the governing factors for not using timber as the tension reinforcement in concrete, but it can be used in concrete slabs as the distribution bars, where the main purpose is crack controlling. In this study, the technical and economic feasibility of using Kithul wood rods as a substitute material for distribution steel in lightly loaded one-way slabs is checked. Testing for material properties of Kithul wood was done according to BS373:1957 standard. Three slab panels having dimensions 1200 mm×600 mm×100 mm was cast using 10 mm×10 mm square Kithul rods and 10 mm diameter steel reinforcing bars. Different arrangements of the distribution reinforcement were considered to identify the flexural behavior of the reinforced concrete one-way slab panels having Kithul wood as distribution reinforcement. All the concrete slab panels were made using grade 25 concrete and after curing for 28 days they were tested for flexure under a 3-point loading test. The control specimen, which has only steel reinforcement showed the highest flexural capacity, whereas the other two slab panels containing Kithul rebars showed a flexural capacity of more than 79% of the flexural capacity of the control specimen. On the other hand, the new slab panels containing Kithul rebars are cost-effective, and with a proper design, they can be used for lightly loaded one-way concrete slabs.

Keywords: Kithul wood rebar; Distribution reinforcement; Renewable material; One-way concrete slab; Flexural strength; Lightly loaded slabs

1. Introduction

Concrete is a widely used construction material in the Civil Engineering industry. Because the concrete is weak in tension, it is used with reinforcement when tensile stresses exceeding the tension capacity of the concrete are expected. Though steel reinforcement is an ideal material for this issue, there are some problems associated with the use of steel such as corrosion. In the production of steel, a huge amount of Carbon Dioxide is emitted (Hasanbeigi & Marlene, 2016). By suitably reducing the usage of steel, Carbon Dioxide emissions due to the production of steel can be minimized. Since steel is not a renewable material and is an expensive material compared to other typical construction materials, alternative materials should be discovered for sustainable development. Today, many researchers seek the feasibility of replacing steel rebar with alternative reinforcing materials such as fiber-reinforced polymer. Kithul (Caryota Urens) is a tree that grows in tropical countries. Normally lifespan of a Kithul tree is about 15 to 20 years. When considering green concepts, trees that ending their life span can be selected for the wood rebar production process. When considering the practical usage of Kithul wood, it shows high strength and durability. Though there is much research about the properties of wood species in Sri Lanka there is a lack of details about the properties of Kithul wood (Pushpakumara, et al., 2023). This research is done to check the feasibility of replacing steel distribution rebars with Kithul wood rebars in one-way spanning slabs. The objectives of this study are to investigate the mechanical properties of locally available Kithul wood and to investigate the flexural behavior of partially reinforced slab panels with Kithul wood and steel rebar.

2. Material Tests on Kithul Wood

2.1. Preparation of Kithul Wood

The well-grown tree should be selected, hardwood should be extracted, and softwood should be removed. Kithul trees start to end their life span normally after 15 years old and such a tree was taken for this study. After the extraction of hardwood from the tree, it is seasoned and sized according to the required dimensions using wood mills. Coatings with Borax are used for Kithul wood preservation, and it is more economical than other chemicals.

2.2. Three-Point Bending Test

A static three-point bending test was carried out to determine the modulus of elasticity of Kithul wood. Figure 1 shows the details of the static bending test. Testing was done according to BS 373:1957 standards of testing small clear specimens of timber (BSI, 1957). The dimensions of the central loading test specimen were $20\,mm \times 20\,mm \times 300\,mm$.

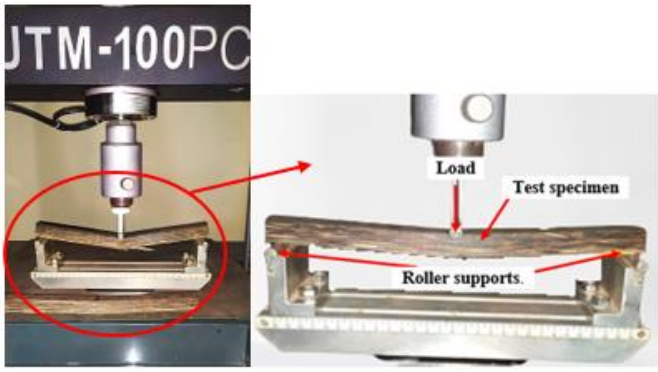


Figure 1: Three-point bending test.

2.3. Compressive Strength Test

Testing was done according to BS 373:1957 standards of testing small clear specimens of timber (BSI, 1957). This test was done both parallel to the grain, and perpendicular to grain. As given in Figure 2, the dimensions of the compression parallel to grain test specimens were $60\ mm \times 20\ mm \times 20\ mm$. The load was applied to both types of test specimens in such a way that the loading plates approach each other at a rate of $0.011\ mm/s$. In compression perpendicular to grain, the test specimen was a $20\ mm$ cube (Figure 3) and the test was done using a universal testing machine (Figure 4). The load was applied to the test specimen at a constant rate, same as the compression parallel to the grain test.

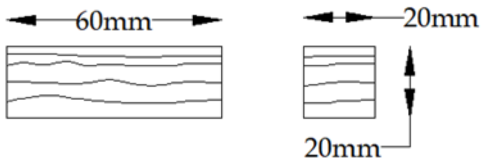


Figure 2: Compression parallel to grain.

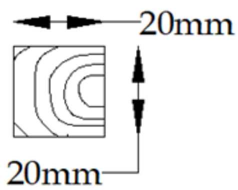


Figure 3: Compression perpendicular to grain.

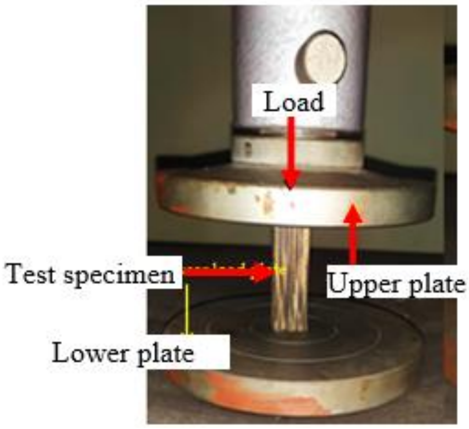


Figure 4: Compression parallel to grain.

2.4. Tensile Strength Test

As shown in Figure 5, the tensile strength test was carried out using a universal testing machine. Here, tension parallel to the grain was determined. Testing was done according to BS 373:1957 standards of testing small clear specimens of timber (BSI, 1957). The form and dimensions of the test specimen used in one method for determining the tension parallel to grain strength are illustrated in Figure 6. The load was applied to the test specimen at a constant head speed of $0.021\ mm/s$.

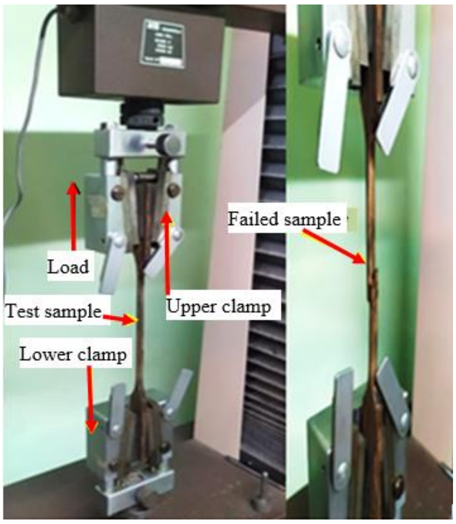


Figure 5: Tensile test parallel to grain.

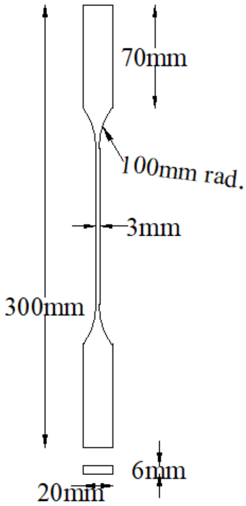
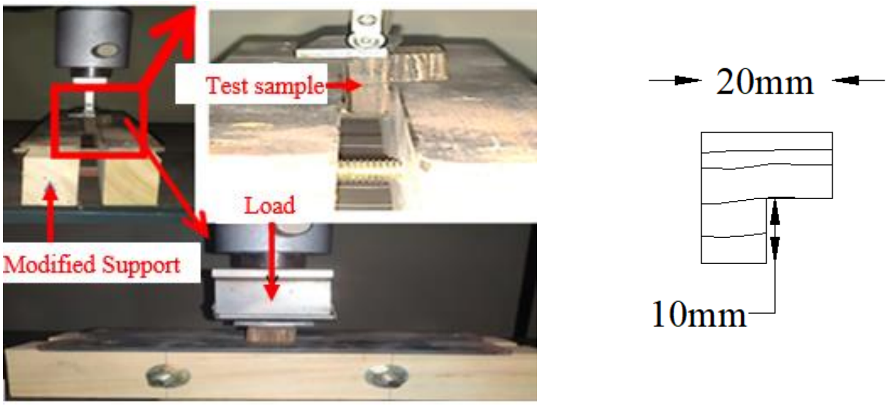


Figure 6: Test specimen of tensile strength test.

2.5. Shear Strength Parallel to Grain Test

Shear strength parallel to grain test was carried out as shown in Figure 7(a). According to BS 373:1957 standard, the size of the shear strength parallel to the grain test specimen is a cube of $20\ mm$. The load was applied at a constant rate of crosshead movement of $0.021\ mm/s$. In this test, the loading was applied parallel to the longitudinal direction of the test specimen and a modified testing setup, and a test specimen were used as shown in Figure 7(b). $10\ mm \times 10\ mm \times 20\ mm$ a portion was removed from the 20 mm cube specimen to stabilize the specimen in the universal testing machine the test was done and there was a little difference from standard size according to BS 373:1957.



(a) Testing setup (b) Specimen

Figure 7: Modified shear parallel to grain test.

3. Experiment on One-way Slab Panels

In this experiment, four slab panels were tested and all the slab panels were of the same size, and they were prepared by changing the distribution reinforcement. The sectional size of Kithul wood reinforcement is $10\ mm \times 10\ mm$ square sections, shown in Figure 8. For the structural design of this special slab system, the guidelines given in BS 8110: Part 1 (BSI, 1985) were used. As shown in Figure 9, the size of a slab panel is $1220\ mm \times 610\ mm \times 100\ mm$. Figure 10 shows the different reinforcement patterns of distribution reinforcement (longer-span direction) with Kithul wood and steel rebar. Grade 25 concrete was used for all the slab panels and Table 1 shows the mix proportions.

Table 1: Mix proportions of grade 25 concrete

Material	**Mass (kg)**
Cement	441.18
Fine aggregate	685.6
Coarse aggregate	1033.4
Water	225.2

Figure 8: Kithul wood rebar $10\ mm \times 10\ mm$ square section.

The panels were cured for 28 days and then tested for flexure. The compressive strength of the panels was determined using the concrete cubes, which were casted with the panels.

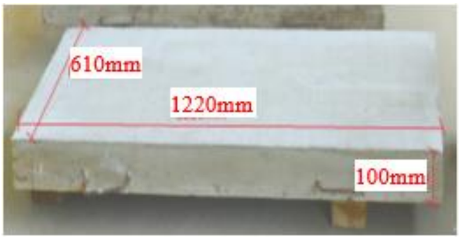


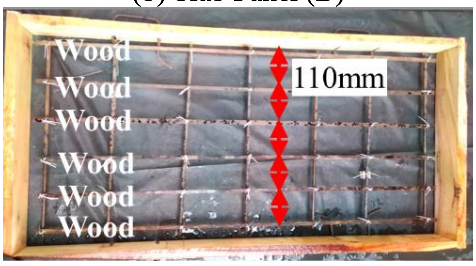
Figure 9: Casted slab panel with dimensions.

Slab Panel A is the control specimen, which was cast using 10 mm diameter tor steel for both shorter and longer-span directions. The tensile strength of the steel rebar is $460N/mm^2$. Other three slab panels were casted with both steel reinforcement and Kithul wood reinforcement. Steel reinforcement was used along the shorter span of the other three slab panels. Kithul wood reinforcement was used along the longer span of the slab panels as distribution reinforcement. The slab panels were marked as Panel (A), Panel (B), Panel (C) and Panel (D). In all the slab panels along shorter span center to center spacing of 10 mm diameter steel reinforcement was 195 mm.

(a) Slab Panel (A)

(b) Slab Panel (B)

(c) Slab Panel (C)



(d) Slab Panel (D)

Figure 10: Reinforcement arrangement slab panels.

To observe the flexural behavior of slab panels, a three-point bending test was conducted. Flexural behaviors of panel (B), panel (C) and panel (D), are compared relative to slab panel (A). The load was applied as a uniformly distributed load (UDL) along the centreline of the shorter span. Load testing on individual slab panels was carried out using the test setup shown in Figure 11 and Figure 12. The flexural test was conducted until the failure of slab panels and the applied load, midspan deflection were recorded throughout the test.

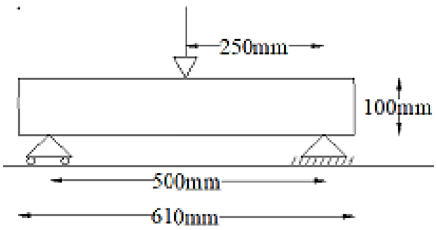


Figure 11: Testing setup schematic diagram.

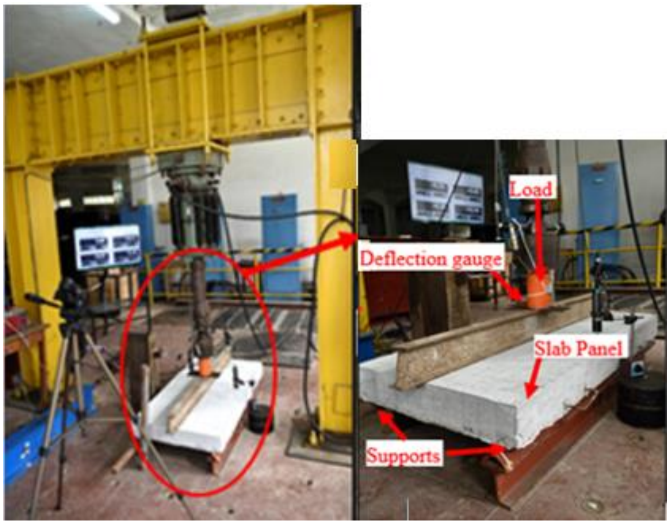


Figure 12: Three-point bending testing setup.

4. Results and Discussion

4.1. Mechanical Properties of Kithul Wood

The density of Kithul wood at 12% moisture content is around 640 kg/m^3 (Ruwanpathirana N, 2016). Results obtained by the testing for Kithul wood are shown in Table: 2. According to test results of Kithul wood samples, Kithul wood has higher bending strength, tensile strength, compressive strength, modulus of elasticity, shear strength values compared with service classes 1 and 2 wood categories given in BS 5268: Part 2: 2002 (BSI, 1984). Kithul wood has a higher tensile strength value and a higher compressive strength value. Therefore, Kithul wood can be classified as service class 1.

Table 2: Mechanical properties of Kithul wood

Property (Parallel to grain)	**Value (N/mm^2)**
Bending strength	96.00
Average tensile strength	144.06
Average compressive strength	64.33
Modulus of elasticity	14000.00
Shear strength	5.48
Property (Perpendicular to grain)	Value (N/mm^2)
Average compressive strength	45

In slab panel A, load at failure is 181.91 kN and deflection at failure is 2.95 mm. Cracks on the top surface of the slab panel started at a load of 150 kN. In slab panel B, load at failure is 94.38 kN and deflection at failure is 1.66 mm. Cracks on the top surface of slab panel B started at a load of 90 kN. This failure can occur due to transfer of a sudden impact. In slab panel C, load at failure is 144.1 kN and deflection at failure is 3.72 mm. Cracks on the top surface of the slab panel started at a load of 141 kN. In slab panel D, load at failure is 160.4 kN and deflection at failure is 3.45 mm. Cracks on the top surface of the slab panel D started at a load of 105 kN.

Table 3: Load carried by slab panels

Panel	Maximum load carried (kN)	Loading percentage compared to Panel A (%)
A	181.91	100
B	91.5	52
C	144.10	79
D	160.40	88

Figure 13 shows the load vs. deflection of four slab panels. According to the results, slab panel A (control specimen) had the maximum flexural capacity. According to the reinforcement arrangement of slab panel A (Figure 10 (a)), steel rebars were used as distribution steel. Slab panel A is a conventional arrangement of slab panels used in the construction industry. When considering slab panel C, has 4 numbers of Kithul wood rebars. Panel C could carry a load of about 79% compared to panel A. There is more stress concentration in square-type rebars than round-shaped rebars. Due to this reason cracks and failure may be different from slab panel A. Also, slab panel D carried a load of 88% compared to the load carried by slab panel A. Slab panel D contained six Kithul wood rebars as distribution rebars. Square-type rebars are used in slab panel D and there may be stress concentration more than round rebars and crack patterns and failure load may be different due to this reason.

According to Figure 13, sudden load reductions occurred in the loading curves of panels A, C, and D. This may have happened due to the occurrence of cracks. When comparing Panel C (100% Kithul wood distribution bars at 175 mm spacing) and Panel D (100% Kithul wood distribution bars at 110 mm spacing) in Figure 13, the stiffness of the slab panel D has been significantly improved. Therefore, stiffness of slab panels can be increased by reducing the spacing of wooden rebars.

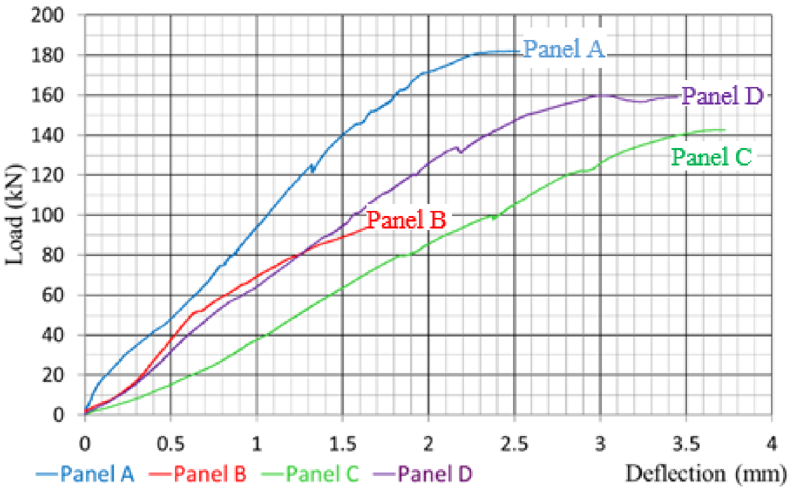


Figure 13: Load vs. deflection of four slab panels.

Figure 14 shows the crack pattern of panel A. Typically in other panels failure also occurred along the UDL after the appearance of the flexural cracks.

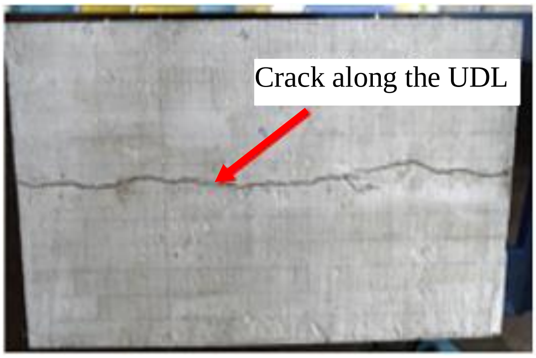


Figure 14: Panel A after the failure.

5. Conclusion and Recommendations

This study was focused on the investigation of the mechanical properties of Kithul wood and the flexural behavior of one-way slab panels using Kithul wood rebars as distribution reinforcement. The main conclusions and recommendations of the study are stated below.

- Kithul wood has a higher tensile strength value and a higher compressive strength value compared to wood taken for structural purposes. Kithul wood can be classified as a service class 1 wood.
- There is a slight reduction in the flexural strength (around 12%) of the slab panel having 100% Kithul Wood distribution bars compared to the slab panels having 100% steel distribution bars.
- The stiffness of slab panels can be significantly increased by reducing the spacing between wooden rebars.
- It is recommended to conduct the testing by changing the cross-sectional shape of the Kithul wood rebars.

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STRUCTURAL FEASIBILITY OF PRECAST FIBER-REINFORCED LIGHTWEIGHT CONCRETE WALL PANELS

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Abstract: Lightweight concrete is one of the newly emerging building construction materials in Sri Lanka and it's becoming popular as it reduces the weight of the structure, ease of handling, reduced cost for finishes, and fast construction. In this study, the suitability of fiber-reinforced lightweight material for the precast partition wall system and its cost-effectiveness were investigated. The Aerated Autoclaved concrete (AAC) was used as the lightweight material and natural Bristle-type coir fiber was used as the fiber-reinforcing material. The lightweight property in AAC is gained by making air entrapped artificially by chemical foaming agents. The main objectives of the study are to identify the optimum coir fiber mix proportion for AAC, which gives the maximum compressive strength, and investigate the flexural behavior of the coir fiber mixed AAC wall panels. The compressive test specimens ($100\ mm \times 100\ mm \times 100\ mm$) were produced by mixing o.5% to 3.0% coir fiber with AAC. Three AAC wall panels having a size of $1200\ mm \times 600\ mm \times 150\ mm$ were tested for lateral loads by BS EN1052: part 2:2016. According to the experiment results, the average flexural strength of the AAC-Coir fiber wall panel was 0.51 N/mm^2. The AAC-Coir fiber wall panels showed significantly high lateral load resisting capacity and it is more than the recommended value given in BS-5628: part 1:1992 for walls constructed with burnt clay bricks which is 0.4 N/mm^2. Therefore, the proposed wall panels can be used for the non-load-bearing partitioning wall construction. According to the cost comparison results, the fiber-reinforced wall panels are cost-effective when compared with the typical AAC wall systems.

Keywords: Lightweight concrete; Precast wall panels; Autoclaved Aerated Concrete; Coir fiber; Flexural strength; Fly ash

1. Introduction

A wide range of materials is used in the construction industry for wall elements. Clay bricks, concrete, cement blocks, soil blocks, and rubble masonry are the most commonly used materials for wall construction in Sri Lanka. Precast wall panels have become popular in fast constructions such as high-rise buildings and mega housing projects. However, most of the available precast wall panels are made of ordinary concrete and do not exhibit lightweight properties. On the other hand, the conventional cement blocks are made of cement-sand mortar mix and weigh 1800 - 2000 kg (Sahir & Samir, 2001) which will result in a heavy load to the weight of the building. In the case of bricks and soil blocks, the continuous use of natural resources for manufacturing has led to many environmental problems. Therefore, the use of waste materials to produce alternative building materials can help for sustainable development in the construction industry. The coal ash (coal fly ash) which is a residual of coal burning processes for power generation has been identified as a waste material, which leads to a massive environmental problem if openly dumped. Therefore, lots of researchers are interested in producing building materials by using coal fly ash. The most popular building material is Aerated Autoclaved Concrete (AAC) which is made out of coal fly ash, cement, water, and some other metallic powders. In this study, the structural behavior of fiber-reinforced Aerated Autoclaved Concrete wall panels is investigated. The precast wall panels were tested under lateral loading and vertical loading and the results were compared with the similar tests which have been carried out for different partition walling materials. The primary objectives of this study are to investigate the optimum coir fiber content for AAC material and to investigate the compressive and flexural capacities of coir fiber reinforced AAC wall panels. The secondary objective is to compare the manufacturing cost of coir fiber reinforced AAC wall panels and other typical wall construction materials.

2. Materials

2.1. Aerated Autoclave Concrete (AAC)

Lightweight concrete can be defined as a type of concrete that includes a foaming agent in it. Aerated concrete is a mortar, with fine sand or industrial waste like fly ash as filling material, in which air is entrapped artificially by chemical foaming agents (metallic powders like Al, Zn). The aerated concrete does not contain coarse aggregate. The Lakvijaya coal power plant of Sri Lanka caters 900 MW to the national grid, and it burns 340 tons of coal per hour. Therefore, the main residual known as fly ash has become a waste material which is been accumulating in huge amounts and leads to severe environmental problems. The power plant has approximately 300,000 tons of fly ash quantity in their dump yard (Figure 2.1).

Figure 2.1: Fly ash duping yard at Lakvijaya coal power plant.

AAC is a mixture of cement, fly ash, sand, water, and Aluminum (Al) powder. The fly ash used in this study is Class F, which contains oxides of Silicon, Aluminum, Iron, and Calcium (Refer to Table 1)

Table 1: Chemical composition of fly ash used

Chemical Composition %											
SiO_2	**Al_2O_3**	**Fe_2O_3**	**CaO**	**MgO**	**Na_2O**	**K_2O**	**P_2O_5**	**TiO_2**	**MnO_2**	**SO3**	**other**
50.93	28.7	3.53	7.42	2.16	0.21	0.61	1.78	1.53	0.02	2.16	0.95

The particle size of 70% of the total volume is smaller than 45 µm and loss of ignition (LOI) is less than 5% based on the performance of the power plant.

Aluminum is the air-entraining agent and the bubbles are formed when the raw materials are mixed, such as 65%-70% of fly ash, 15%-20% of Lime, 8% of cement, and 0.08% of Aluminum powder. In this study, a water-cement ratio of 0.6 was maintained. The air bubbles are introduced due to a reaction between calcium hydroxide and Aluminum, and as a result, Hydrogen gas is released (Hamad, 2014). As a result of the Hydrogen gas bubbles, the volume of the raw mix is increased. As shown in Figure 2.2, these gas bubbles make the air-entrained structure at the end of the process.

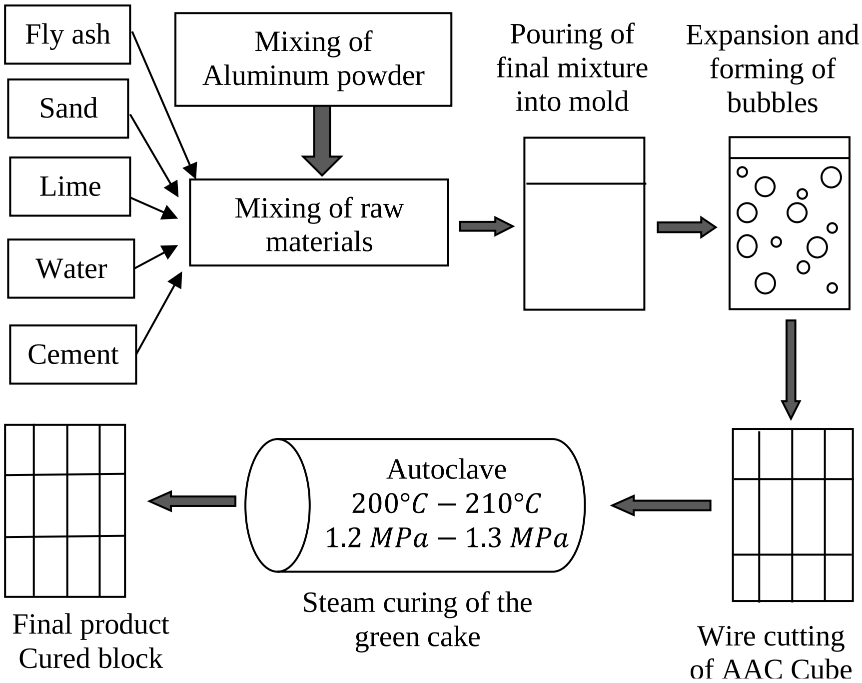


Figure 2.2: Manufacturing process of AAC.

At the end of the foaming process, part of the Hydrogen gas escapes into the atmosphere. When the gas is removed from the material, it is solid but still soft. It is then cut into blocks and placed in a cylindrical chamber for 11-12 hours for steam curing under $200°C - 210°C$. Figure 2.3 shows the wire cut AAC cube before steam curing.

Figure 2.3: AAC cube before steam curing.

2.2. Coir Fibres

The coir fibers, also known as coconut fibers, are natural fibers extracted from the coconut husk. Coir fibers are one of the thickest and strongest natural fibers in the world. These fibers are easily available as coir fiber production is a large industry in the country. There are four main types of coconut fibers in Sri Lanka, namely, Bristle fiber, Omat fiber, Mattress fiber, and mixed fibers. The standard of Sri Lankan coir fiber is presented in 'Sri Lankan standard for mechanically extracted coir fibers' (SLS 115 Part 1, 2019). Coir fiber is a hygroscopic material that can absorb moisture. The breaking load is the maximum force applied on the fiber when broken in tension. The tensile strength is expressed as breaking load per unit cross-sectional area of the fiber strand and the tests were done by Samarawikrama (2010). The selected bristle-type coir fiber has an average strength of $126.95\ N/mm^2$ and average breaking load is $4.96\ kN$.

Figure 2.4: Bristle-type coir fiber.

3. Experimental Program

A detailed experimental procedure was carried out to achieve the research objectives and the compressive strength test was carried out to determine the fiber mix proportion that yields the highest compressive strength for the coir fiber reinforced AAC material. AAC-coir fiber wall panels were constructed with optimum fiber percentage with AAC material to test the flexural strength and compressive strength. A cost comparison was made for the coir fiber reinforced AAC material with other conventional walling materials.

3.1. Optimum Fiber Percentage for AAC Material

The coir fibers were taken from a coir mill and experimental samples were produced at an Aerated Autoclaved Concrete manufacturing facility. $25\ mm - 30\ mm$ pieces of Bristle fiber were used for cube casting. The range of coir fiber in $1.5\%, 2.0\%, 2.5\%,$ and 3.0% by the weight of the solid part of AAC material were added to make the test cubes. Three specimens of $100\ mm \times 100\ mm \times 100\ mm$ were cast from each coir fiber percentage. The control specimen was made only with AAC material. All cubes were steam cured in an unautoclaved chamber at $190°C$ for 8 hours. The green cake (partially hardened AAC), just after pouring of coir fiber and AAC mixture into a mold is illustrated in Figure 3.1. The AAC test cubes were tested for compressive strength after 28 days after casting.

Figure 3.1: Casting fiber-reinforced AAC cubes.

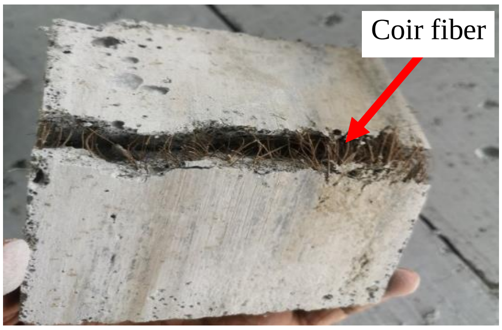


Figure 3.2: Distribution of coir fibers in AAC material.

3.2. Flexural Strength of Wall Panels

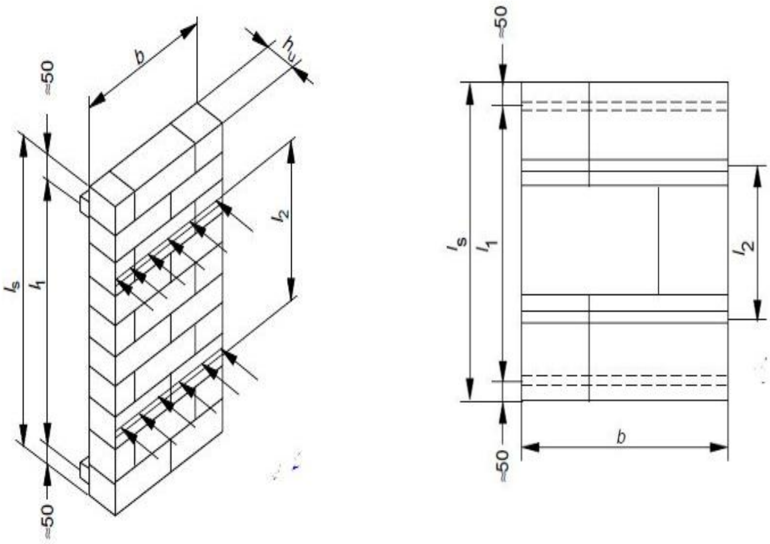
To incorporate the practical limitations, scale-downed panel specimens were prepared for testing. The selected panel size was $1200\ mm \times 600\ mm \times 150\ mm$. A timber mould was prepared. As shown in Figure 3.3, when the AAC mixture was poured into the mold, the coir fiber pieces were added to the wet AAC mixture simultaneously and mixed with the slurry evenly.

Figure 3.3: Casting coir fiber reinforced AAC wall panels.

The AAC wall panels were tested for both flexural and vertical compressive strength. There is no clear guideline to test AAC walls and hence the procedure provided in BS EN1052: part 2 (2016) for masonry wall panels was adopted. The dimensions of the specimen are decided according to the code recommendations. Two panels were tested for each test of flexural strength and compressive strength.

The flexural strength of a wall is important when subjected to a lateral load such as wind, flood, or any other load that causes the bending of a wall. The flexural strength is tested by loading the panels laterally while the constant compressive load is applied vertically to the specimen. The test apparatus was set up according to the guideline provided in BS EN1052: Part 2 (2016) for masonry walls as shown in Figure 3.4.

In this test series, a pre-compression load ($1.24\ kN$, self-weight of a $1.8\ m$ high AAC panel, see Figure 3.5) was applied to simulate the actual conditions. This was done using a hydraulic jack mounted on the top side of the wall panel, connected with a load cell. The pre-compression limited the stress likely to occur at the top level of the tested wall panel due to the self-weight of the AAC wall segment which will be placed above during actual construction. As shown in Figure 3.5, the vertical load was applied as a UDL using a rigid steel member.



$$b = 600\,mm, h_u = 150\,mm, l_s = 1200\,mm,$$
$$l_1 = 50\,mm, \quad l_2 = 600\,mm$$

Figure 3.4: Standard dimensions of panels used for determining the flexural strength.

While applying the pre-compression load, the panels were tested for the lateral loading by the four-point loading method. The loading jack was set up so that its axis of the loading goes through the geometric center (midpoint) of the panel (Figure 3.5). A dial gauge was fixed at the midpoint of the bearing rods to measure the deformation at the midpoint of the wall panel. The lateral load was applied at a rate of $0.026\,kN/s$ and the dial gauge reading, applied lateral load, applied vertical load (pre-compression load), and the time was recorded until the specimen failure.

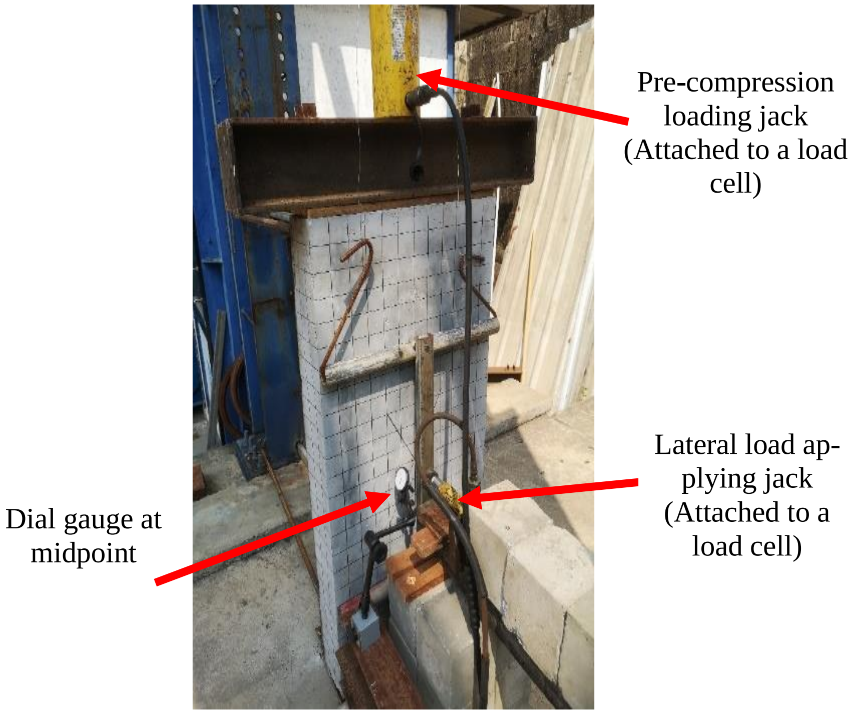


Figure 3.5: A wall panel being tested for flexural strength parallel to the bed joint.

3.3. Compressive Strength of Wall Panels

Two wall panels having dimensions of $1200\ mm \times 450\ mm \times 150\ mm$ were tested for compressive strength The specimen panels were constructed with the same coir fiber percentage ($2.5\%\ /was$for the flexural strength test. The panel was loaded from the top through a load cell by a hydraulic jack. Twodial gauges were fixed to measure vertical deflection and the bending parallel to the bed joint as shown in Figure 3.6.

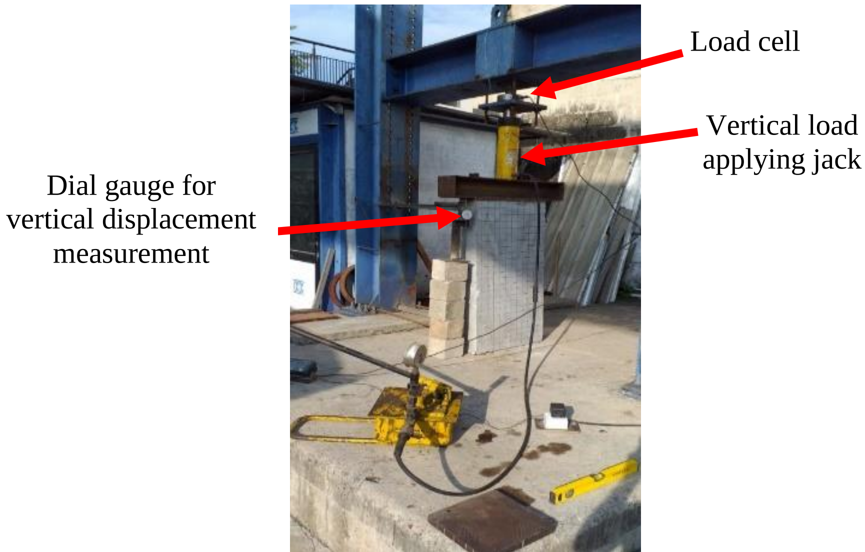


Figure 3.6: Wall panel being tested for compressive strength.

4. Results and Discussion

4.1. Compressive Strength Test of Coir Fiber-Reinforced AAC Cubes

Table 2 shows the compressive strength test results of coir fiber-reinforced AAC cubes. The maximum compressive strength ($4.41\ N/mm^2$) was observed in AAC material having 2.5% coir fiber with the base material. Therefore, the optimum fiber percentage is taken as 2.5% from the weight of the solid part of the AAC material. AAC material has relatively low tensile and flexural strength due to its ceramic-like nature. As a result, brittle failure may occur. Coir fiber reinforcement improves the resistance to the split of the composite material since it provides tensile strength on cracks and enhances the material interlock of concrete. Therefore, the compressive strength is increased due to the increased split resistance of the concrete cube. The strength depends on the volume of the concrete surrounding the fibers. High fiber content reduces the volume of the surrounding concrete–matrix and may create voids (because of clumping) in the concrete, which will cause a reduction in the compressive strength. The distribution of coir fiber in AAC material is shown in Figure 3.2.

4.2. Flexural Strength Test Results of Wall Panels

Figure 4.1 shows the relationship between lateral load and the deflection at the midpoint of the wall panels 1, 2, and 3. The failure load is considered at the appearance of the first crack of the panel, when the lateral load is applied. Wall panels 1 and 2 are identically constructed and the used coir fiber percentage is 2.5%. Wall Panel 3 is the control specimen, and it did not contain coir fibers.

Table 2: Compressive strength of Coir fiber reinforced AAC cubes.

Fiber Percentage (%)	Average Compressive Strength (N/mm^2)
0.0	2.13
1.5	2.90
2.0	3.49
2.5	4.41
3.0	3.61

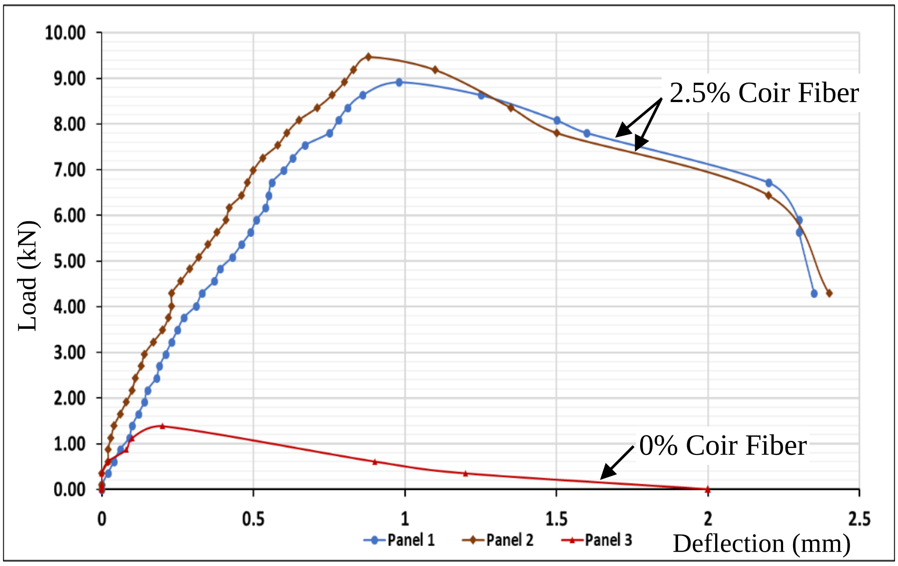


Figure 4.1: Applied load Vs deflection for three specimens.

The characteristic flexural strength of wall specimen f_{xi} is expressed as a function of failure load and panel dimensions. The flexural strength is calculated by using the following Eq. (1) provided in BS EN1052: Part 2;2016.

$$f_{xi} = 3F_{i,max}(l_1 - l_2)/2bt_u^2 \qquad (1)$$

Where,

$F_{i,max}$ – Maximum failure load, l_1 – Spacing between supports

l_2 – Spacing between loading points, T_u – Thickness of panel

b – Width of the panel

The calculated characteristic flexural strengths of wall panels are shown in Table 3. Coir fiber reinforced AAC panels showed six times flexural strength improvement compared to the control specimen. However, the density of AAC material in Panels 1 and 2 was increased compared to that of the control specimen due to the removal of some air bubbles during the coir fiber mixing process.

Table 3: Flexural strength test results of AAC wall panels.

Test	Panel 1 (Fiber 2.5%)	Panel 2 (Fiber 2.5%)	Average (Fiber 2.5%)	Panel 3 (No fibers added)
Flexural Strength parallel to bed (N/mm^2)	0.50	0.52	0.51	0.08

4.3. Compressive Strength Test Results of Wall Panels

The wall specimens of fiber-reinforced AAC also showed a significant improvement in compressive strength. The test results of the compressive strength test are listed in Table 4. It has been found that the compressive strength was significantly improved by 78% when the coir fiber was used. The coir fiber has high tensile strength and it increases the compressive strength of the AAC panel by preventing micro-cracks, enhancing toughness, and increasing energy absorption capacity.

Table 4: Compressive strength test results of wall panels.

Panel No.	Applied Maximum Lateral Load (kN)	Compressive Strength (N/mm^2)	Average Compressive Strength (N/mm^2)
Panel 1 (2.5% fiber)	275	>3.05	>3.08
Panel 2 (2.5% fiber)	280	>3.11	
Panel 3 (0% fiber)	156	1.73	1.73

5. Cost Comparison

Cost comparison for the construction of conventional partitioning walls and the wall finishes per one square meter was done according to the building schedule of rates published in 2022 by the Department of Buildings, Sri Lanka (Department of Building Sri Lanka, 2022) and the Rates of Building Works for 2022, published by Chief secretary's office, North Western Provincial Council. For the cost comparison, six wall types were considered, 1) $150\ mm$ thick Cellular (Hollow) block masonry, 2) $150\ mm$ thick solid block masonry, 3) Brickwork in cement mortar (1:5) (Burnt clay bricks), 4) Precast cellular concrete panels, 5) $150\ mm$ thick AAC block masonry, and 6) $150\ mm$ thick Coir fiber-reinforced AAC wall panels. And also, a $15\ mm$ thick plastering to the wall (cement and sand 1:5, semi-rough finished, both sides of the wall panel) and apply 'skim coat' compound on walls (two coats), finished smooth with sandpapering, and prepare for color washing were considered for cost calculation.

A cost comparison for the construction of locally available concrete partitioning wall panels was done according to the manufacturer's details. (ICC (Pvt) Ltd, 2012). A cost comparison for the construction of the Aerated Autoclave concrete brick wall was done according to the manufacturer's pricing details and the actual labor costs.

Table 5: Cost comparison for conventional partitioning wall constructions per square meter in Sri Lankan rupees (LKR).

Types of walls	Cost per m^2 (LKR)			Total cost per m^2
	Materials and Workmanship	Plastering (Two sides)	Finishes (Two sides)	
150 mm thick Cellular (Hollow) block masonry	3087.00	1792.00	1096.00	5374.00
150 mm thick solid block masonry	2987.00	1792.00	1096.00	5875.00
Brickwork in cement mortar (1:5) up to 1 cube, on the ground floor	3736.00	1792.00	1096.00	6624.00
Precast cellular concrete panels	5280.00	-	1096.00	6376.00
150 mm thick Aerated Autoclave Concrete (AAC) block masonry	5980.00	-	1096.00	7076.00
150 mm thick coir fiber reinforced AAC wall panels	4794.00	-	1096.00	6161.00

6. Conclusions

The compressive strength and the flexural strength of wall panels made out of coir fiber-reinforced Aerated Autoclaved Concrete have been reviewed in the research.

- Use of coir fiber in AAC significantly improved the compressive strength and the optimum mix proportion of coir fiber is 2.5%.
- Adding 2.5% of coir fiber gives high lateral load resistance capacity and it is more than the recommended value given in BS-5628: Part 1:1992 for walls constructed with burnt clay bricks (0.4 N/mm^2). The flexural strength of coir fiber-reinforced AAC wall panels is significantly (around six times) higher than that of the AAC panels without coir fibers.
- There is around a 78% increase in compressive strength of coir fiber-reinforced AAC panels compared to no-fiber AAC panels. Therefore, these panels can be proposed for the non-load-bearing and load-bearing walls.
- Coir fiber-reinforced AAC wall panels are cost-effective compared to typical AAC block masonry.

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EFFECTIVENESS OF IMPLEMENTING SUSTAINABLE PUBLIC PROCUREMENT (SPP) PRACTICES IN THE SRI LANKAN CONSTRUCTION INDUSTRY

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Abstract: The need for adequate public procurement practices has imposed several construction industry issues, leading to project delays and inefficient use of public funds. To improve the situation, Sustainable Public Procurement (SPP) practices would be a better start position on revival. However, the literature review emphasizes limited studies conducted on SPP practices related to the construction industry in Sri Lanka. Hence, the primary focus of the research revolved around crafting an implementation framework for SPP practices within the Sri Lankan construction industry, aiming to address existing gaps and promote greater sustainability and responsible procurement practices within the sector. A detailed literature review was conducted to identify and prioritize challenges and key drivers in implementing SPP practices in local and foreign construction industries. A pre-survey was conducted with ten government personnel working in the construction industry to assess their awareness and identify challenges and key drivers faced by SPP practices in the construction industry. Pre-survey and literature review results were used to develop the proposed framework and validated through an online survey. Thirty-four responses were collected from government and semi-government officials in the construction industry. Four responses were discarded due to irrelevant answers, and 30 were used for data analysis. Based on the data analysis, ten challenges and six key drivers were used to develop the framework. The implementation framework was created with the support of a literature review and the feedback of subject matter experts (SME). The subject matter experts reviewed and validated the framework, and feedback was incorporated. The results of this study benefit policymakers and institutional practitioners handling construction procurement works.

Keywords: Construction industry; Public procurement; Sustainable public procurement practices

1. Introduction

The Sustainable Public Procurement (SPP) process refers to acquiring goods, services, works, and utilities for public use, focusing on benefiting society and the economy while minimizing environmental harm. Acknowledging the construction industry's negative impact on the environment, natural resources, and public health underscores the need for Sustainable Procurement (SP) practices (Abduh, 2018). Therefore, improving SPP practices would be a better starting point for revival. Indeed, beyond individual initiatives, there is a growing global impetus to promote SPP practices in the construction industry. SPP goes beyond just Green Public Procurement (GPP) and encompasses various other essential aspects such as Social Return of Investment (SRI), Circular Economy (CE), Bio-based Public Procurement (BPP), Innovation-Oriented Public Procurement (IOPP), and International Social Criteria (ISC). These diverse components collectively contribute to a comprehensive and holistic approach to SP practices (Grandia & Voncken, 2019). Public Procurement (PP) contributes 15% - 20% to the national revenue globally (Bamfo et al., 2018), which focuses on buying goods and services for the needs of the public (Uyarra & Flanagan, 2009). Due to harsh environmental and socio-economic impacts, most governments fail to maintain due diligence, pressure, corruption, and legal losses (Preuss, 2009). Countries have identified the implementation of SPP as a powerful solution to reduce corruption and economic improvements in the country (Akenroye et al., 2013). Researchers have conducted various studies on SPP practices in the construction industry, such as identifying possible challenges, barriers, benefits, best practices (Amarapathy et al., 2013), model development (Ewuga, 2017), legal base, and instrument support (Kozik et al., 2016). SPP practices are firmly established in the construction industry in developed countries (Opoku & Fortune, 2013). However, researchers have discussed awareness improvements and challenges in establishing SPP practices in developing countries like Nigeria (Akenroye et al., 2013) and Malaysia (Bohari et al., 2015). Still, only some can be found in the Sri Lankan context. None of the papers discussed implementing SPP practices in the Sri Lankan construction industry, particularly during pre-construction. The absence of such discussions highlights the need for further research and attention to address this specific aspect of SP practices in the construction sector in Sri Lanka. During the 19th amendment to the constitution of Sri Lanka, several steps were taken to enhance the country's PP process (CIDA, 2015). The main objective was to improve the PP process and enhance project delivery with minimum public corruption. As a result of the constitution, the Construction Industry Development Authority (CIDA) was established to facilitate construction industry activities in Sri Lanka (CIDA, 2015). Further, the study by Athapaththu & Karunasena (2017) revealed that adopting SPP practices in Sri Lankan contracting organizations is in the primary stage, and the need for a procurement strategy and legitimate framework is a gap in the pp in Sri Lanka (Gunawardena, 2016). The unavailability of procurement regulatory bodies, lack of governance engagement, and ineffective capacity building have identified gaps in PP in the construction industry. Therefore, this study aims to derive a framework for implementing SPP practices. Aligning with the research gap, the main research objective was derived as,
"To evaluate the contribution to the national benefits of implementing Sustainable Public Procurement (SPP) practices in the Sri Lankan construction industry."

Moreover, derived sub-objectives: Identify the challenges and key drivers to implement SPP practices in the construction industry and develop a feasible framework for implementing SPP practices in the construction industry.

At first, we conducted a literature review and identified 16 challenges and seven key drivers. Then, we used a pre-survey to identify context-specific challenges or key drivers. Then, the online survey was developed based on the findings and shared with government and semi-government organizations involved with the construction industry's PP activities. Out of 34 respondents, four were discarded due to irrelevant answers. Exploratory and descriptive methods were followed for data analysis of the research, and ten prioritized challenges and six key drivers for implementing SPP practices were derived. We used the results to develop the SPP practice framework and verified with ten Subject Matter Experts (SME) identified through snowball sampling. The rest of the paper is organized as follows. Related work and research methodology are presented in sections 2 and 3, respectively. Then, the data analysis is in section 4, a set of recommendations is in section 5, future work is in section 6, and a conclusion is in section 7.

2. Related work

The construction sector heavily relies on natural resources (Abduh et al., 2018). Therefore, developing SP practices is essential for minimizing ecological impact (Jayalath & Gunawardhana, 2017). Public Procurement (PP) practices are directly linked to the country's economic development (Gunawardhane & Karunasena, 2015). Contractors have embraced sustainability to adhere to environmental standards at construction sites (Gunawardhane & Karunasena, 2014), with SP practices demonstrating substantial influence across both public and private sectors (Gunawardhane & Karunasena, 2014). Sustainable Public Procurement (SPP) practices within the construction industry are key for economic growth in Sri Lanka's construction sector, contributing significantly to overall progress (Gunawardhane & Karunasena, 2016). The most acceptable method to solve the issues in PP practices is the application of SPP practices (Gunawardhane & Karunasena, 2015) in Sri Lanka. However, there are challenges and key drivers to be considered in SPP implementation.

2.1 Challenges and Drivers identified in SPP Implementation

Other than the environmental practices, SPP should also focus on social and economic practices. Much research has been conducted on identifying challenges in implementing GPP in developing countries (Khan et al., 2018); (Bohari et al., 2015). Therefore, this research considered both GPP and SPP research results to identify the challenges in SPP practice implementation. Existing research studies covered different areas (i.e., barriers, challenges, enablers, drivers, and factors impacting the implementation of SPP practices).

In both GPP and SPP implementation, *Lack of awareness/Knowledge on SPP practice* and *Lack of Training/ Lack of educational qualification and professional experience* have become significant issues (Wirahadikusumah et al., 2020); (Ogunsanyaa et al., 2019); (Mensah, 2012); (Khan et al., 2018); (Bohari et al., 2015); (Bidin et al., 2020); (Bohari et al., 2019); (Bidin et al., 2019)) because without having a proper understanding of SPP concepts people would not be able to support the SPP practice implementation (Rais, 2018). Due to the unavailability of standard guidelines and procedures, establishing and maintaining SPP practices takes time and effort. Based on the research work carried out by Bohari (2019), Bidin et al. (2019), Alqadami et al. (2020), and Akenroye et al. (2013) have identified the *Lack of standard guidelines* as another significant challenge. Initially, the government should focus more on addressing policy iterations while retaining an environmentally focused approach (Gunawardhane & Karunasena, 2014). *Lack of enforcement* is another obstacle to implementing SPP practices discussed by the researchers (Gunawardhane & Karunasena, 2015); (Gunawardhane & Karunasena, 2014); (Akenroye et al., 2013); (Bidin et al., 2019); (Bohari et al., 2015); (Silva et al.; U., 2022)). The researchers have defined the *lack of enforcement* in different ways. Gunawardhane and Karunasena (2015) have described it as *the absence of support from top management*. To establish SPP, a high initial cost is required. To find funds, top management enforcement is essential. Moreover, the government should take the cost and benefit of social, economic, and environmental for sustainable improvement of the economy (Gunawardhane & Karunasena, 2015). Moreover, researchers have identified a *Lack of funding* as a challenge to implement SPP practices in construction (Gunawardhane & Karunasena, 2015); (Bidin et al., 2019). Further, the study conducted by Bohari (2019) has identified stakeholders' possible strategies, such as setting up policy guidelines, improving knowledge on green procurement, carrot and stick approach, client, and top management commitment, and enhancing capacity building among construction players. Bidin et al. (2019), in their SWOT analysis conducted for GPP practices, have identified weaknesses: lack of funding, research and development, and commitment and demand. *High cost of respective products and services* ((Khan et al., 2018) ; (Bohari et al., 2019)), *Passive culture* ((Khan et al., 2018); (Brammer & Walker, March 2011)), *Insufficient tools* ((Bohari et al., 2019); (Khan et al., 2018)) *Issues in policy formation and actual project delivery* ((Khan et al., 2018); (Bidin et al., 2020)), *Technical and technological difficulties* (Bohari et al., 2019), *Lack of upper management support in a company/ Lack of Leadership* ((Khan et al., 2018); (Bidin et al., 2020); (Brammer & Walker, March 2011)), *Resistance to change* (Brammer & Walker, March 2011), *Lack of trust on the security of the tools* (Bohari et al., 2019), *Insufficient co-operation with academia and environmental organizations* ((Khan et al., 2018); (Bidin et al., 2019); (Akenroye et al., 2013)) are another set of challenges captured in the literature. Several key drivers in the construction industry, such as *organizational leadership*, *government policies*, *financial incentives*, *legislation and regulations*, and *client demand*, encourage the implementation of SPP practices. *Compliance with legislation*, *organizational structural processes*, *political willingness*, and *adoption of global strategy* are drivers for implementing SPP practices in the study (Ogunsanyaa et al., 2019). Other than challenges and key drivers, we also research the benefits of using SPP practices.

2.2 Benefits of the Use of SPP Practices

Reducing the impact caused by toxic material on human health, meeting existing and forthcoming legislation around the climate change agenda, reducing harmful emissions and waste generation, improving working conditions and labor standards, health, and safety, assisting disadvantaged groups of society, upskilling the workforce to meet the future needs of the organization, saving the long term by considering the whole Life Cycle Cost (LCC), meet international obligations, improving the efficiency and transparency of procurement procedures, stimulate the market for green technology are the list of benefits identified by Perera, (2007). Gunawardhane and Karunasena (2015) emphasized the importance of considering the Triple Bottom Line (TBL) policy to balance and maximize positive outcomes across all three dimensions. SPP practices are a widely accepted alternative successfully implemented in developed countries (Gunawardhane & Karunasena, 2015). Moreover, Mohan (2010) has identified seven key benefits of adopting Sustainable Public (SP) practices. These benefits include controlling costs considering the broader whole-life costs approach, achieving internal and external standards, ensuring compliance with environmental and social legislation, managing risks and enhancing the organization's reputation, creating new vibrant markets, ensuring future supply security, and maximizing community and financial benefits. After studying the existing research, we finalized the steps to derive the identified objectives.

3. Research Methodology

This research mainly focused on developing a framework to implement SPP practices for the construction industry. The study was conducted in exploratory and descriptive methods. At first, we studied literature to understand the steps followed in framework development. Indonesia’s construction industry is new to the implementation of SPP practices. After analyzing the literature review, they have identified that customizing the existing framework is more feasible than working on a fresh framework (Muhamad et al., 2018). Asian Development Bank (ADB) has introduced a procurement cycle to be followed to improve the SPP process (Development Bank, 2021). Moreover, Muhamad et al. (2018) discussed framework development for SP in Indonesian companies' construction industry. The researcher has followed the explorative approach due to the topic’s novelty and limitations in SP practices and plans. In their research, Athapaththu and Karunasena (2017) used a case study approach after identifying C1 grade companies where C1 is the highest grade of contractors in Sri Lanka. Finally, the developed framework has been validated with the support of seven United Arab Emirates and Sri Lanka SMEs with 5+ years of experience in sustainable construction projects.

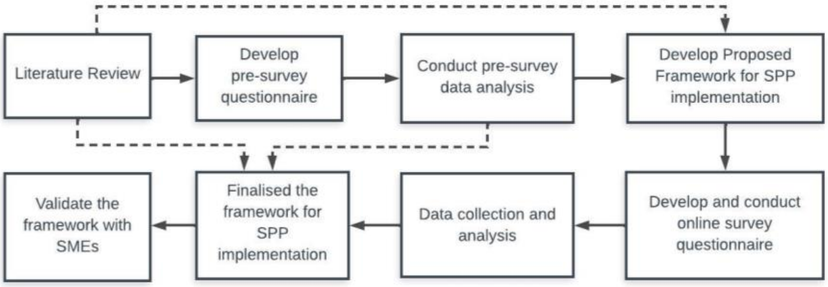

Figure 1: Research methodology – Steps followed to achieve the research objectives.

After analyzing the framework development methodologies followed in research papers, we finalized the framework identified in Figure 1. Initially, a literature review identified the key challenges and drivers' impact on SPP practice implementation. After that, a pre-survey was conducted to determine any challenge and driver impact on SPP practice performance in the Sri Lankan context. In snowball sampling, we selected ten SMEs to understand the construction industry’s current state. The pre-survey questionnaire was developed based on the literature review findings. Then, an online survey was conducted to validate the proposed framework. The online survey questionnaire was developed considering the literature review and pre-survey results. The survey was shared with government and semi-government employees involved in construction procurement work. Based on the results analysis, the SPP practice implementation framework was finalized. The framework was reviewed with face-to-face interviews conducted with 10 SMEs and updated after incorporating the SMEs’ feedback. Finally, more interviews were conducted with SMEs from different procurement fields to generalize the framework to the Sri Lankan context.

3.1 Data Collection

Initially, the literature review was conducted to identify the challenges of implementing SPP practices. After scanning through 70+ research papers, 16 challenges were identified. The pre-survey highlighted no specific challenge or key driver context to Sri Lanka. The online survey consists of eight demographic questions, six weighted questions, two ranking questions, and two general questions to capture expert knowledge for the case. Strongly Agree, Agree, Disagree, and Strongly Disagree are the weights used for the questions. Respondents were given five minutes to answer the questionnaire. We received 34 responses and deleted four due to irrelevant responses. Based on the data analysis, results were used to develop the framework to implement the SPP practices for the construction industry. After that, semi-structured interviews with 10 SMEs were conducted to validate the framework, and feedback was incorporated for framework improvements. To maintain consistency and to improve the quality, we refer to the same ten SMEs selected using snowball sampling (Mack et al., 2005).

4. Data Analysis

Though we received 34 responses, four were removed due to irrelevant answers, and 30 responses were considered for data analysis. Only 21% of the respondents are from Senior Management (i.e., Deputy General Manager (DGM) or Additional Finance Manager (AFM)), and the rest are playing executive-level roles, i.e., Engineer, Accountant, Architect, and Quantity Surveyor (QS). 100% (30) of the respondents recommend the pre-construction stage (ref. Figure 2) for SPP practices in the construction industry. 96% of the respondents agreed that achieving value for money, improving stakeholders' ethical behavior, and ensuring fairness and transparency are benefits identified after implementing the SPP process.

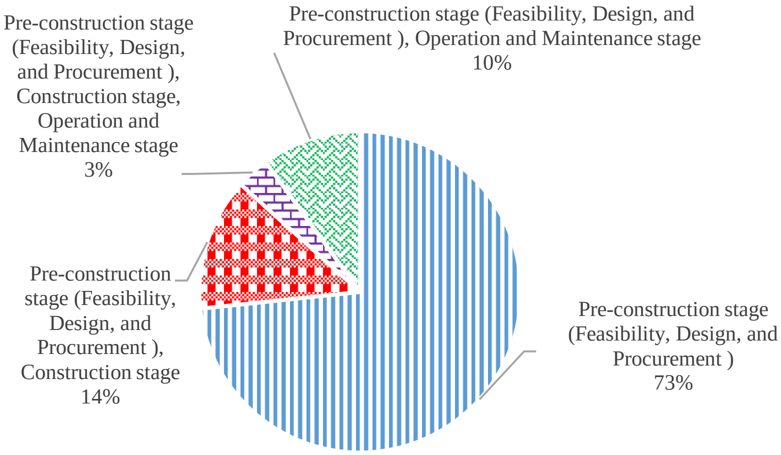

Figure 2: Based on the responses, the best stage to apply SPP practice implementation in the construction industry.

The responses for the 16 challenges and seven key drivers were weighted considering 4, 3, 2, and 1 weightage for the strongly agree, agree, disagree, and strongly disagree Likert scale. There was a 1% strong disagreement for the challenges of *Lack of Funding*, *Lack of Enforcement*, *High cost of respective products and services*, *Passive culture*, *Insufficient tools*, *Technical and technological difficulties*, and *Lack of trust in the security of the devices*. The highest disagreement for the challenge of the cost of respective products and services is 28%. The rest of the challenges have less than 28% of disagreements. Therefore, every challenge must be considered out of 16 collected through literature review and pre-survey. When considering the combination of 'Strongly Agree' and 'Agree' choices, *Issues in policy formulation and actual project delivery* and *Lack of* enforcement are the most rated challenges (96%), and the *High cost of respective products and services* is the lowest-rated challenge (72%). *Lack of Knowledge/ awareness of SPP practices, Mismatch of procurement strategy and national policy/absence of a clear national IT policy*, *Insufficient cooperation with academia and environmental organizations*, and *Resistance to change* challenges have 94%, 93%, 93%, and 92% ratings, respectively. There are six challenges with a rating of more than 90%. Further, based on the respondents' preferences, sixteen challenges were prioritized, considering the impact on the implementation of SPP practice. We identified that *Lack of Knowledge/awareness of SPP practices*, *Lack of enforcement*, and *Issues in policy formulation and actual project delivery* challenges have priority with 75% of respondents' preference. *Lack of Funding*, *Mismatch of procurement strategy and national policy/Absence of a clear national IT policy*, and *Resistance to change* challenges have second priority with 60% of respondents' preference. Moreover, we found that semi-government and government respondents have two preferences against prioritizing 16 challenges. For government respondents, a *Mismatch of procurement strategy and national policy/Absence of a clear national IT policy*, *Insufficient cooperation with academia and environmental organizations*, *Lack of Training*, and *Insufficient Research and Development* challenges are the most preferred (100%). For semi-government respondents, policy formulation and project delivery issues are the highest priority challenges (100%).

Besides the challenges, out of seven key drivers, only the *Politicians* have 65% preference with 35% disagreement (a combination of "Strongly disagree" and "disagree"). *Procurement and engineering professionals* (100%) and *Government Regulatory entities* (100%) are the most preferred key drivers. *Professional organizations* have 96% preference. *Non-government organizations*, *Civil society organizations*, and *Contractor organizations* have 76%, 73%, and 70% preference, respectively. We removed Politicians from the list and considered the six key drivers for implementing SPP practices in the construction industry. SME also suggested removing *Politicians* as it received a lower percentage than the others.

4.1 Framework Design

We prioritized ten challenges for framework development, considering the respondents' preference in Table 1 to develop the SPPP framework. For the ten prioritized challenges, the "sum of weights" and preference in both government and semi-government have more than 80% other than the semi-government preference of priority 9 and 10 have 76% and 74%, respectively. Face-to-face interviews were conducted with ten SMEs who participated in the pre-survey to get feedback on our results. Seven are from semi-government organizations, and three are from government organizations. SME recommends prioritizing ten challenges as initial implementation rather than focusing on all 16 challenges.

Table 1: Prioritised challenges against respondents' preference

#	Challenge	Respondents' Preference
1	Mismatch of procurement strategy and national policy/Absence of a clear national IT policy	75%
2	Insufficient cooperation with academia and environmental organizations	75%
3	Lack of Training	75%
4	Insufficient Research and Development	60%
5	Lack of Enforcement	60%
6	Insufficient tools	60%
7	Lack of upper management support in a company. / Lack of Leadership	55%
8	Lack of Knowledge/awareness of SPP practices	55%
9	Resistance to change	50%
10	Lack of Funding	50%
11	Issues in policy formulation and actual project delivery	50%
12	Lack of trust in security due to tools	45%
13	Technical and technological difficulties	45%
14	Lack of Standard Guidelines	45%
15	Passive culture	45%
16	High cost of respective products and services	30%

Framework (ref. figure 3) was validated through an online survey and face-to-face interviews with the ten (10) SMEs involved in the pre-survey. Seven Civil engineers, one chief Quantity surveyor, and two Chief Engineers served as SMEs.

The following recommendations were suggested during the face-to-face interviews with the ten SMEs.

1. SME suggested realigning the framework, adhering to the priority of the challenges received at the online survey.
2. SME suggested identifying the factors that align with the Triple Bottom Line (TBL).
3. 0Because "politicians" had only 35% responses for disagreement (a combination of Strongly disagree and disagree), it is better not to use Politicians for framework design.
4. It is recommended to follow the PDCA approach with the expectation of frequent changes to the framework as it is set up for the first time.

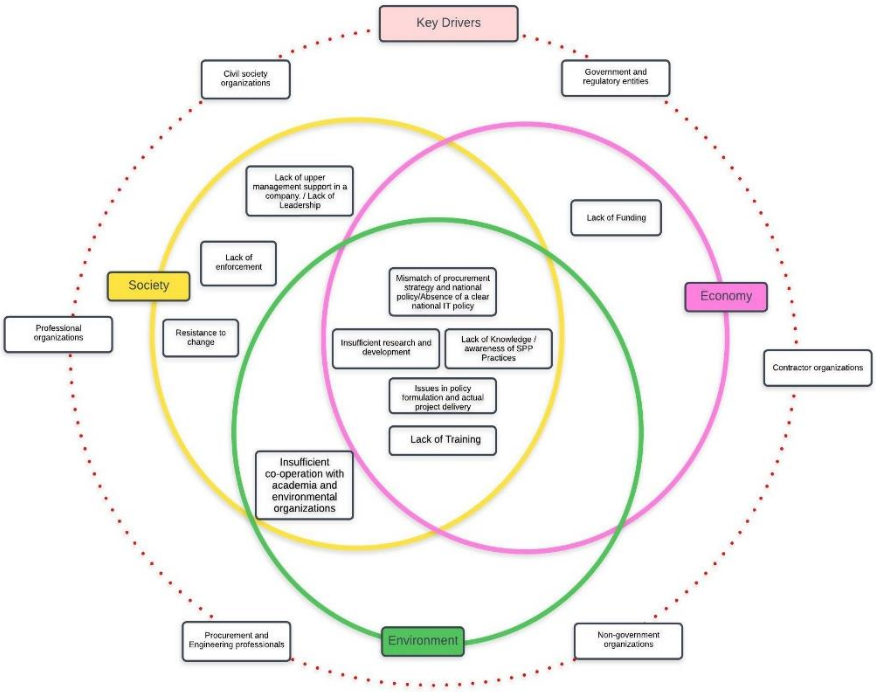

Figure 3: Finalised framework for SPP implementation. – TBL was considered in developing the framework.

4.2 Research Findings Vs. Research Objectives

The main research objective, sub-objectives, and respective research findings are illustrated in Table 2. There are two research sub-objectives, and all two sub-objectives were achieved. Further, additional research findings were listed respectively.

Table 2: Mapping of research findings against research objectives and other research findings

<table>
<tr><th>Research Objectives</th><th>Achievement of research objectives – results</th></tr>
<tr><td>Identify the challenges and key drivers to implement sustainable public procurement practices in the construction industry.</td><td>After conducting a literature review, pre-survey, and online survey, 16 challenges and seven key drivers were identified.</td></tr>
<tr><td>Develop a feasible framework for implementing sustainable public procurement practices in the construction industry.</td><td>The framework was developed using ten challenges and six key drivers.</td></tr>
<tr><td colspan="2">Other Findings</td></tr>
<tr><td colspan="2">1. 100% of the respondents agreed that the Pre-construction stage is the best stage to start work on the SPP practice implementation.
2. 86% of the respondents conduct virtual meetings/ seminars.
3. National Competitive Bidding (NCB) is the procurement method all respondents use.
4. Achieve value for money, sustaining economic Development, Improving the Ethical behavior of stakeholders, Reducing harmful emissions and waste generation, Ensuring fairness and transparency, and Enhancing the quality and quantity of Government construction projects are the expected benefits after the implementation of SPP practices has received 96%, 92%, 96%, 91%, 96%, 95% preferences, respectively.</td></tr>
</table>

5. Recommendations

In most developing countries, SPP has yet to be implemented. Therefore, it is recommended to use the framework for SPP implementation illustrated in Figure 3 for the construction industry in developing countries like Sri Lanka. Moreover, the developed framework needs to be introduced to the national decision-makers who are involved in the PP work. Results emphasized that the best stage to implement SPP is the pre-construction stage. The research identified six key drivers and recommended engaging within the framework wherever necessary. Further, it is recommended to follow a systematic approach such as the Plan-Do-Check-Act (PDCA) approach in mitigating the identified challenges. At the 'Plan' stage, once the project is identified to execute for SPP implementation, the project scope needs to be finalized, and project governance needs to be set up with the help of key drivers. It is recommended to conduct training workshops to mitigate the *Lack of knowledge/awareness of SPP practices* and *Lack of training*. Setting up the policy framework was the other important task. Government must closely work with external organizations, such as non-government organizations, Contractor organizations, Procurement and engineering professionals, Government regulatory entities, Civil society organizations, and Professional organizations to enhance research and development to prepare procurement strategy and national policy. At the 'Do' stage, mitigate the four challenges (i.e., *Resistance to change*, *Lack of upper management support in a company*/ *Lack of leadership*, *Lack of funding*, and *Lack of enforcement*) iteratively. The government must put more effort into overcoming *resistance to change* challenges. The PDCA approach is an iterative process; therefore, based on the review and feedback gained at the end of each iteration, it should be used to improve the next iteration. Research and development must be followed at each iteration with the support of key drivers. Finally, implementation must be executed at the "Act" stage of the selected project, focusing on continuous improvement.

6. Future Works

While this research derives a framework to implement SPP practices in the construction industry, further research must be carried out to validate the defined strategy after execution in construction projects in different environments. Out of 16 challenges and seven key drivers, it was considered to prioritize 10 challenges and seven key drivers. Therefore, it would be better to reconsider the rest of the challenges and drivers. The identified framework should be practiced in other industries as well. However, further studies need to be conducted to identify more challenges and key drivers before starting to work on applying for the rest of the sectors.

7. Conclusion

We identified ten prioritized challenges and six key drivers impacting the SPP practice implementation in the pre-construction stage in Sri Lanka. Based on the findings, we developed the SPP framework illustrated in Figure 3 and validated it with 10 SMEs identified from the construction industry. Moreover, benefits expected after implementation of SPP practices were identified as achieving value for money, sustaining economic development, improving the ethical behavior of stakeholders, reducing harmful emissions and waste generation, Ensuring fairness and transparency, and Enhance quality and quantity of Government construction projects with 96%, 92%, 96%, 91%, 96%, 95% respondents preferences, respectively. It is recommended to utilize the identified framework of SPP implementation for the construction industry in developing countries like Sri Lanka, where such implementation has yet to be conducted. We are in the process of identifying a suitable project to start work on the SPP practice framework.

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EXPLORING URBAN WALKABILITY: AN ASSESSMENT OF SIDEWALKS AND PEDESTRIAN FACILITIES IN PUBLIC TRANSPORT DISTRICTS; IN ACCORDANCE WITH THE GREEN SL® RATING SYSTEM FOR SUSTAINABLE CITIES THE CASE OF PETTAH, SRI LANKA

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Abstract: Within the realm of sustainable city development, Public Transport Districts (PTD) emerge as a crucial focal point, exerting a profound influence on the dynamics of urban spaces. Central to this consideration is the concept of walkability, which underscores the critical importance of optimizing sidewalks and pedestrian facilities to enhance pedestrian-centric and high-quality transport landscapes. The primary objective of this research is to develop a detailed walkability evaluation framework by examining the Green SL® Rating System for Sustainable Cities by the Green Building Council of Sri Lanka—a tool designed to recognize and foster sustainable urban development practices within Sri Lanka. Grasping the requirements set by the Green SL® Rating System for Sustainable Cities, the developed framework is centered around three primary walkability factors: 1) Design and Infrastructure, 2) Safety and Traffic Conditions, and 3) Proximity and Land Uses. For empirical insights, a case study was conducted in the public transport district of Pettah in Colombo, Sri Lanka—a bustling economic center that integrates various public transportation services. This case study utilizes a qualitative analysis approach involving on-site observations and visual surveys, aiming to answer the central research question: "To what extent do the existing sidewalks and pedestrian facilities within public transport districts promote walkability?". The findings from the case study reveal a significant gap: despite favorable proximity and land use attributes, inadequacies in design, infrastructure, safety, and traffic conditions collectively contribute to suboptimal walkability conditions within the case study area, rendering these spaces less favorable for pedestrian activities. It is expected that the findings will provide guidelines for respected parties to increase the efficiency of walking and the quality of pedestrian environments, ultimately resonating with the broader aspiration for sustainable cities.

Keywords: Walkability; Public Transport District; Sidewalks; Pedestrian Facilities; Sustainable Cities

1. Introduction

Urbanization is a defining trend of the 21st century, with over half of the global population now residing in cities (Ritchie & Roser, 2018). While cities offer economic opportunities and cultural richness, they also grapple with numerous challenges, including traffic congestion, pollution, and social disparities. Sustainable city development seeks to address these issues by planning and developing urban environments that are environmentally responsible, socially inclusive, and economically viable, ultimately enhancing overall quality of life. Public Transport Districts have emerged as significant contributors to this endeavor, as they reduce carbon emissions, alleviate traffic congestion, and improve accessibility to essential services. At the heart of their effective operation lies the fundamental concept of walkability. A city designed with thoughtful consideration for walkability offers a range of pedestrian-friendly amenities, which in turn fosters more sustainable urban environments by reducing dependence on motor vehicles, promoting economic prosperity, enhancing public health, facilitating social interactions, and promoting inclusivity.

This study focuses on the GreenSL® Rating System for Sustainable Cities, designed to recognize and promote sustainable urban development practices in Sri Lanka. Given its emphasis on sidewalks and pedestrian facilities in advancing sustainable transportation, this research aims to seamlessly integrate these requirements with identified walkability parameters. The objective is to create a more detailed assessment framework that prioritizes walkability as a central component of sustainable city development. By addressing the research question, "To what extent do the existing sidewalks and pedestrian facilities within public transport districts promote walkability?", this study ensures the practical applicability of the original rating system across diverse local urban environments. The integration of such multidisciplinary approaches in walkability frameworks will also yield more standardized assessment outcomes (Woo et al., 2018), filling existing gaps in the literature.

2. Review of Literature

The literature review primarily centers on examining the integration of walkable public transport districts within the sustainable city development framework. It also entails a detailed analysis of the criteria outlined in the Green SL® Rating System, particularly concerning sustainable transportation goals.

2.1 Sustainable City Development and Public Transport Districts

Sustainable city development is defined as designing to address the social, environmental, and economic value of cities through better planning and management (The Zebra, 2003). Five dimensions of sustainable development include environment, economy, spatial, culture, and management. Notably, the spatial dimension takes precedence, directly impacting environmental standards, optimal urban scale, and energy conservation (Telsaç & Kandeğer, 2022), forming the focus of this study. Among many functions performed by cities, transportation plays a major role by enabling the effective movement of people, products, and services within and between city neighborhoods (Geography Notes, 2014). Public Transport Districts in this regard act as specific geographic areas that are designated for the planning, development, and operation of public transportation services. They are characterized by well-planned, transit-oriented infrastructure, typically centered around a major transit hub—a bus terminal, a train station, etc (Lamour et al., 2019).

2.2 Walkability and the Built Environmental Concerns

The physical description of sustainable public transport districts places significant emphasis on walkability. It entails creating urban environments that are highly pedestrian-friendly with seamless and functional connections between land uses and pedestrian spaces (Dittmar, H., & Poticha, 2004). Walkability hinges on the physical elements of the built environment. Referring to Knapskog et al. (2019) and other scholarly works, this research categorizes three main walkability principles: 1) Design and Infrastructure, 2) Safety and Traffic Conditions, and 3) Proximity and Land Uses.

Design and infrastructure refer to the physical design components of urban environments that facilitate convenient and enjoyable pedestrian movement. This includes the provision and unobstructed maintenance of crucial elements such as sidewalks and interior pathways (National Association of City Transport Officials, n.d.), strategically placed pedestrian crossings; especially well-marked crossovers (Redmond Washington, n.d.), and signs and signals to navigable spaces (WalkBoston, 2015). Universal design considerations such as accessible ramps, curb cuts, and tactile paving are also vital for walkability as they profoundly impact who can comfortably use a route (Knapskog et al., 2019). Proper lighting, street amenities like furniture, ample seating, waste receptacles, public washrooms, and green infrastructure further enhance the overall walking experience (Global Designing Cities Initiative, 2023). *Safety and traffic conditions* are paramount in ensuring a secure pedestrian experience (Knapskog et al., 2019). This involves the provision of safe intersections, with effectively managed traffic volumes, and speed control measures like speed limits. Traffic calming features like speed bumps, roundabouts, chicanes, and medians are also important features (San Francisco Department of Public Health, 2008). *Proximity and land use* stimulate how efficient and pleasant it is to walk. This highlights the need for an urban structure at a pedestrian scale. Having easy transport options within walkable distances, mixed land uses, surroundings and activities, and a variety of destinations provide a coherent pedestrian network and a vibrant street life that is worthwhile to walk in (Knapskog et al., 2019).

2.3 GreenSL® Rating System for Sustainable Cities

Global Sustainable Rating Systems for cities serve as comprehensive frameworks to assess and measure the sustainability performance in urban areas. One noteworthy system is the Green SL® Rating System for Sustainable Cities, developed by the Green Building Council of Sri Lanka. This study focuses on its transportation segment, particularly emphasizing sidewalks, and pedestrian facilities, which collectively contribute three crucial points to the rating system. This perfectly aligns with the central theme of the research, aiming to encourage walking as a primary mode of transportation by establishing a seamless pedestrian network. The Green SL® requirements are divided into three segments in the research: pedestrian facilities, sidewalk conditions, and pedestrian safety features. Under *pedestrian facilities*, the requirement is to encompass all relevant elements with careful attention to physical details like width, shading, and pavement type. Additionally, destinations and transport terminals are integral components of the urban layout. Regarding *sidewalk conditions*, the emphasis is on providing adequately spacious sidewalks, characterized by continuous, durable surfaces, with a minimum width of 1.5m on either side of the roads or a minimum of 2.0m on one side for highly trafficked roads. Finally, in terms of *pedestrian safety*, the requirements encompass the provision of ample safety measures in crossings, including properly marked crossings, push-button-operated signals, grade-separated crossings, and speed tables. In addition, the implementation of other safety protocols like the presence of traffic police is also important (Green Building Council of Sri Lanka, 2018).

3. Research Methodology

The research methodology outlines the structured approach employed to investigate the subject matter. It is designed to construct an integrated evaluation framework and subsequently apply it in a selected context for empirical insights as shown in Figure 1.

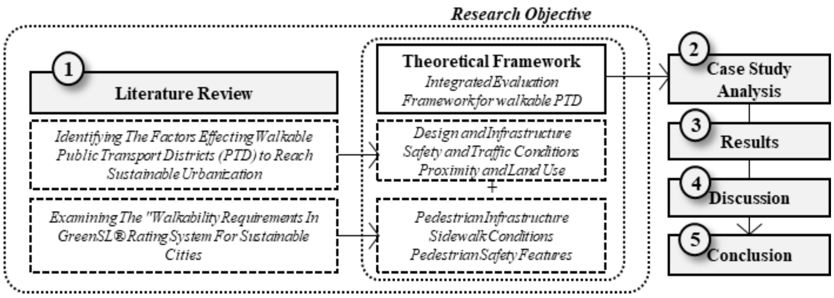

Figure 1: Research Methodology.

3.1 Theoretical Framework

Based on the literature discussed above, the research has integrated the pertinent walkability attributes, deemed most relevant in our context, into the requirements of the Green SL® Rating System as shown in Table 1.

Table 1: Theoretical Framework

Parameters to Check (From Walkability Literature)		From Green SL® Rating
1. Design and Infra-structure	Presence of sidewalks and pedestrian pathways.	a. Pedestrian Infra-structure
	Presence of wider, well-maintained sidewalks.	b. Sidewalk Conditions
	Crosswalks and pedestrian signals for safe crossings.	a. Pedestrian Infra-structure
	Accessibility features like ramps, curb cuts, and tactile paving.	
	Street lighting and visibility for pedestrians, especially at night.	
	Availability of amenities like street furniture, ample seating, waste receptacles, public washrooms, and green infrastructure.	
2. Safety and Traffic Conditions	Low traffic speeds and volumes to reduce the pedestrian risks.	c. Pedestrian Safety Features
	Traffic calming measures like speed bumps or chicanes.	
	Separation of pedestrian and vehicular traffic.	
	Safety measures at pedestrian crossings like proper markings, push-button operated signals, grade-separated crossings, and speed tables.	
	Introducing pedestrian paths to shorten the access and increase public convenience in reaching destinations.	
	Liaising with traffic police.	
3. Proximity and Land Use	Integration of public transportation options within walking distances.	a. Pedestrian Infra-structure
	Access to essential destinations like schools, stores, and public transit.	
	Mixed land uses to reduce the need for long car trips.	
	Availability of parks, green spaces, and recreational areas.	

3.2 Case Study

This case study focuses on the practical application of an evaluation framework to assess the sidewalks and pedestrian facilities within a local public transport district. Colombo was chosen as the research context due to its many challenges like overcrowding, ad-hoc developments, and a chaotic transport landscape (Dayaratne, 2011). Within Colombo, Pettah emerges as a focal point, serving as a major transport hub strategically centered around the Colombo Fort Railway Station. While facilitating a diverse array of public transport modes, Pettah's dynamic and diverse urban environment further amplifies its importance. Given the scope and time limitations of the research, the site boundaries were constrained to encompass the major transport hubs (Fort Railway Station, Major Private Bus Stop in front of the Railway Station, Bastian Bus Stand, Ceylon Transport Board Bus Stand, and Gunasinghepura Bus Stand) and the connected street network (01. Olcott Mawatha, 02. Railway Station Entry Road, 03. W.E. Bastian Mawatha, 04. Saunders Place, 04. Bodhiraja Mawatha and Other Cross Streets), as indicated in Figure 2.

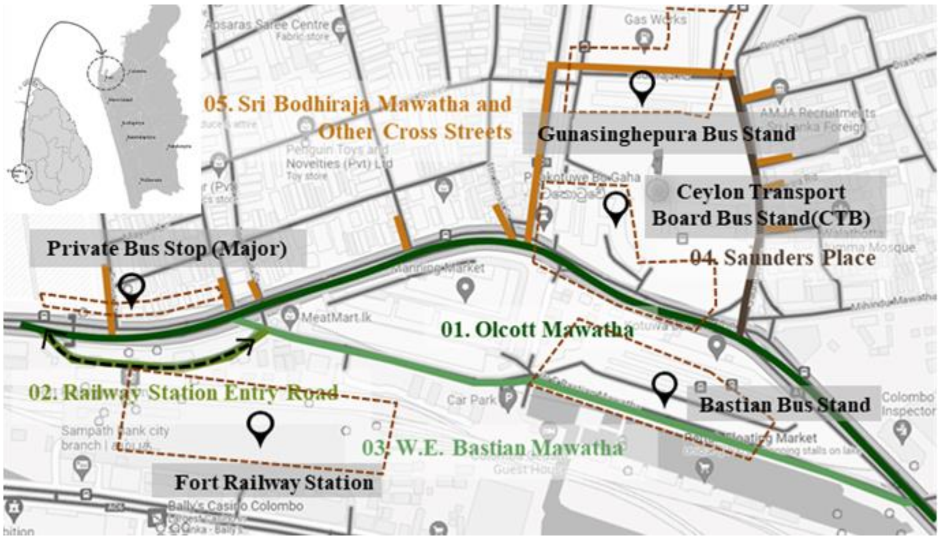

Figure 2: Pettah - Location Map and Site Boundaries.

3.3 Data Collection Methods

This research adopts a qualitative analysis methodology, integrating on-site observations and visual documentation to scrutinize the physical structures and activities within the study area. Using the complete observer method, the researcher objectively observed the environment and human behavior without interference, leading to more precise and sincere depictions of daily life (Kawulich, 2012). Visual documentation encompassed detailed field notes, precise maps, and intricate sketches, supplemented by the crucial use of photography. It is intended that data from photography can help better comprehend onsite processes by capturing nuanced details.

4. Results

Figure 3: Existing Site Conditions.

Figure 3 illustrates the existing site conditions documented during observations. Accordingly, it was noted that all surveyed streets - Olcott Mawatha, Railway Station Entry Road, W.E. Bastian Mawatha, Saunders Place, Bodhiraja Mawatha, and Other Cross Streets - are equipped with sidewalks and pedestrian pathways. The original design specifications allocate approximately 2.0 meters for highly motorized thoroughfares like Olcott Mawatha, W.E. Bastian Mawatha, and Saunders Place, and roughly 1.5 meters for less motorized routes such as Railway Station Entry Road, Bodhiraja Mawatha, and Other Cross Streets. Regrettably, the current condition presents challenges (Figures 4, 5, and 6). Particularly in segments of Olcott Mawatha (around Pettah Cross Street Junctions) and W.E. Bastian Mawatha (near the Railway Station), pedestrian movement is impeded by various obstructions, mainly arising from commercial activities. Furthermore, Railway Station Entry Road exhibits suboptimal conditions, featuring slippery surfaces near the railway station, and obstructions caused by either garbage or storefronts along the rest of the route. Saunders Place poses its own set of challenges, with obstacles such as poorly positioned light poles and uneven surfaces, further exacerbated by obstructive shopfronts. Moreover, some trees along sidewalks appear to be disturbing the pedestrian movement along sidewalks. The issue is most pronounced on Bodhiraja Mawatha and other crosswalks, where commercial activities and shopfronts encroach entirely upon the sidewalks. This compels pedestrians to share the narrow roadways with motorized vehicles, thus creating a hazardous environment. Figure 7 illustrates some commonly observed sidewalk obstructions mentioned here.

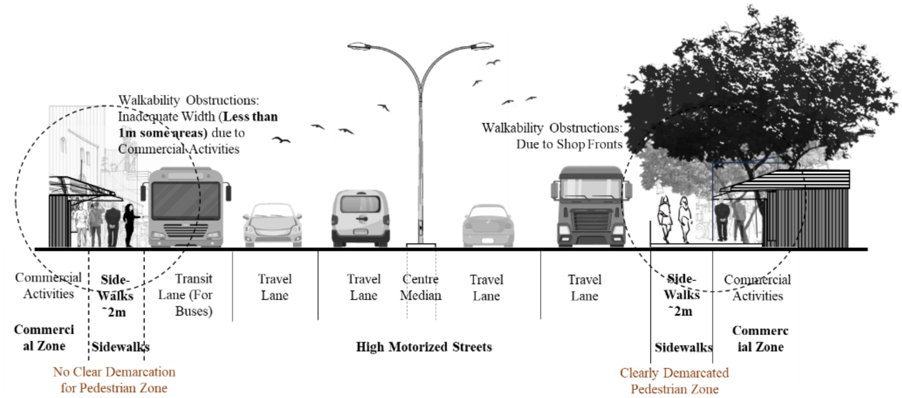

Figure 4: Existing Section Along Olcott Mawatha.

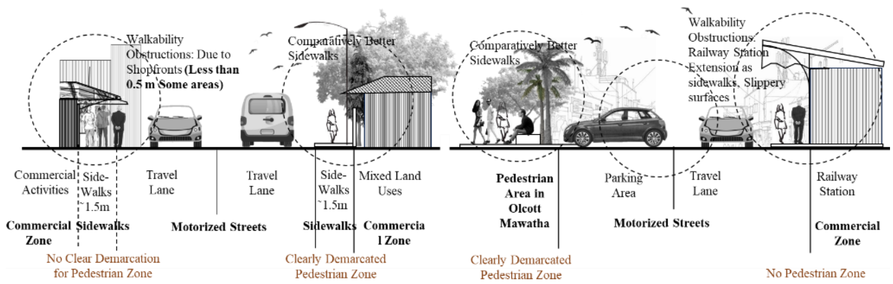

Figure 5: Existing Section Along Railway Station Entry Road (Right) and B.E. Bastian Mawatha Near Railway Station (Left).

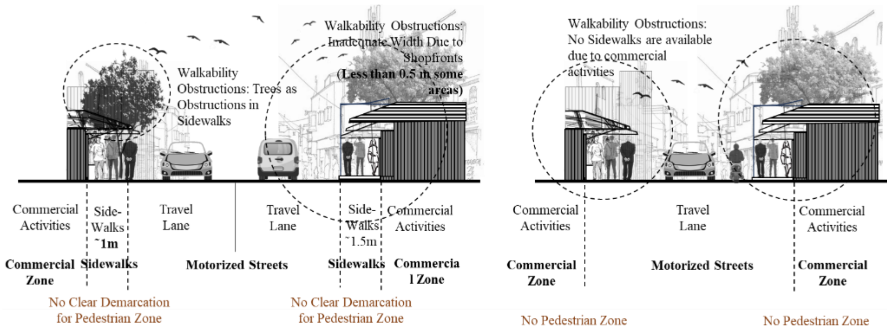

Figure 6: Existing Section Along Saunders Place (Right), Bodhiraja Mawatha, and Other Cross Streets (Left).

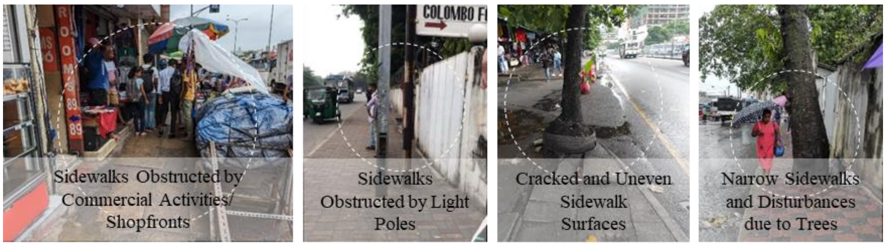

Figure 7: Existing Sidewalk Conditions.

The examination of crosswalks and pedestrian signals reiterates that they are well-implemented along Olcott Mawatha and W.E. Bastian Mawatha. However, along Railway Station Entry Road, Saunders Place, and notably Bodhiraja Mawatha and other Crosswalks, the absence of safe crossings and essential pedestrian signals impedes a comfortable walking experience. While curb cuts are plentiful across all surveyed areas, it is evident that ramps are a crucial missing feature in most locations. Particularly around the Railway Station Entry Road, existing ramps are poorly designed, exhibiting slippery and unfinished surfaces. Moreover, the absence of ramps in W.E. Bastian Mawatha presents significant challenges for pedestrians navigating sidewalks with level changes. Even in Olcott Mawatha, Saunders Place, Bodhiraja Mawatha, and other Cross Streets, improved walkability conditions can be ensured with more ramps, especially around access points for transport facilities, with a focus on their maintenance and surface conditions. The lack of tactile paving is a critical observation, underscoring the barriers to walkability for pedestrians with physical impairments. Figure 8 provides visual documentation of observed crosswalk obstructions.

Figure 8: Existing Crosswalk Obstructions.

The presence of active street lighting during evening and night hours is a positive observation, enhancing visibility for pedestrians. Moreover, shopfronts also contribute to the illumination. However, upon closer examination of essential pedestrian amenities, it becomes evident that provisions for street furniture, seating, waste receptacles, public washrooms, and green infrastructure are woefully inadequate to cater to pedestrian flow. Remarkably, commendable amenities are primarily concentrated around Olcott Mawatha, adjacent to the Railway Station, and W.E. Bastian Mawatha (Figure 9), underscoring a significant negligence in other areas.

Figure 9: Existing Pedestrian Amenities.

While navigating the remaining pedestrian zones along Olcott Mawatha, Saunders Place, Bodhiraja Mawatha, and Other Cross Streets, pedestrians are notably inconvenienced by the absence of seating areas and ample shade. This transforms what should be a comfortable stroll into a wearying journey. Specifically, along Railway Station Entry Road, the critical absence of such amenities hinders walkability in a major transit hub for pedestrians traveling to and from long distances. In summarizing the observations, a significant deficiency in the design and infrastructure essential for walkability within the case study area is evident, leading to less favorable conditions for pedestrian movement. Notably, Olcott Mawatha and W.E. Bastian Mawatha distinguish themselves for their comparatively better design and infrastructure conditions.

Consequently, this analysis emphasizes the pressing need for focused initiatives aimed at enhancing design and infrastructure, thereby promoting the walkability of Pettah's current transport district.

4.2 Safety and Traffic Conditions

The case study underscores the prevalent safety and traffic challenges that significantly impede walkability within the Pettah public transport district. A heavy traffic volume is commonly observed along Olcott Mawatha and Saunders Place while the rest of the surveyed areas had an average traffic volume. However, when it comes to traffic speed, it is evident that none of the surveyed areas have adequate control measures where in certain instances around Olcott Mawatha, W.E. Bastian Mawatha, and Saunders Place, private buses contend with the rest of the traffic, creating exceedingly hazardous conditions for pedestrians. While Olcott Mawatha features center medians (Figure 10) and offers a somewhat accommodating crossing experience, the rest remain ill-suited for pedestrians. The rest of the essential pedestrian infrastructure like speed bumps and chicanes are not found in any of the surveyed areas. Upon careful examination of safe pedestrian zones, it becomes evident that certain sections of Olcott Mawatha and W.E. Bastian Mawatha excel in offering well-defined pedestrian areas (Figure 10), thereby significantly enhancing safety for walkers. However, the remaining surveyed areas, including Railway Station Entry Road and Saunders Place, exhibit inadequate separation between pedestrian and traffic zones (Figure 11). The situation is particularly critical on Bodhiraja Mawatha and Other Cross Streets, where pedestrians are compelled to share the same space with motor vehicles, creating extremely hazardous conditions for pedestrians (Figure 11). In terms of safety measures at pedestrian crossings, along Olcott Mawatha and W.E. Bastian Mawatha, properly marked crossing locations are observed. Most of the crossings at Railway Station Entry Road, Saunders Place, Bodhiraja Mawatha, and other Cross Streets have however vanished or are completely missing, with poor crossing conditions. None of the surveyed areas contain push-button-operated signals and speed tables to ensure a more convenient crossing experience. However, the provision of an overpass in Olcott Mawatha in front of the Fort railway Station is a commendable grade separation crossing feature, which facilitates safe and easy crossing for the heavy pedestrian flow (Figure 10). Importantly, it is noted that the many Cross Streets can serve as potential alternative pedestrian routes, offering more direct access and convenience in reaching destinations. However, their current state is compromised by inadequate sidewalks, unsafe crossing conditions, and poor pedestrian amenities, rendering them unsafe. However, the collaboration between the Pettah Public Transport district and traffic police is on a positive note. The presence of officers in Olcott Mawatha, B.E. Bastian Mawatha, and Saunders Place signifies a commitment to navigating traffic and enhancing pedestrian safety. Along Railway Station Entry Road, Bodhiraja Mawatha, and other Cross Streets also, Police officers are observed, ensuring pedestrian safety (Figure 10).

Summing up, the analysis highlights a pressing concern for pedestrian safety and traffic conditions within the Pettah public transport district. Urgent action is imperative, calling for strategic planning and robust maintenance approaches to foster a truly walkable urban environment.

Figure 10: Existing Safety and Traffic Conditions.

Figure 11: Existing Conditions of Pedestrian Zones.

4.3 Proximity and Land Use

Comparatively, the analysis of proximity and land use in the Pettah public transport district reveals a positive picture. While the first two walkability factors present challenges, proximity, and land use emerge as commendable elements that contribute to the potential for Pettah to become a vibrant public transport district, fostering walkability. As stated previously, figure 2 illustrates that the surveyed street network is positioned around numerous public transportation options with easily walkable distances to and from each route. This accessibility ensures that pedestrians have convenient access to a diverse array of transit choices, facilitating seamless mobility within the city. What is more, Pettah is made up of a dynamic and diverse urban landscape, as indicated in Figure 12 with mixed land uses. This leads to easy access to various essential destinations (see Figure 13) when using transportation services, thereby reducing the necessity for lengthy journeys. Despite these positive aspects, there remains room for enhancement. One notable area for improvement is the availability of accessible parks and green spaces. In the surveyed areas, only certain sections of Olcott Mawatha and W.E. Bastian Mawatha have adequate green spaces. The remaining portions along Olcott Mawatha, Railway Station Entry Road, Saunders Place, Bodhiraja Mawatha, and Other Cross Streets have very few green spaces, which diminishes pedestrian comfort. Moreover, parks and other recreational areas are also observed to be lacking whereas Olcott Mawatha and B.E. Bastian Mawatha had some better parklets and recreational areas (Floating Market).

Figure 12: Proximity and Land Use Map of Public Transport Hubs.

Figure 13: Few Popular Destination Spaces with 1km Radius Distance from Fort Railway Station.

Overall, the analysis underscores that Pettah's proximity and land use are major factors in shaping its walkability. By strategically incorporating more green spaces, Pettah can elevate its walkability, creating a more pleasant and engaging experience for all who navigate its streets. The integration of more greenery can also significantly promote psychological well-being and increase social interactions among pedestrians (Jennings & Bamkole, 2019).

5. Discussion

Discussing the major findings in the previous section, Table 2 indicates the critical built environmental conditions identified, which significantly diminish the walkability within the surveyed streets of the Pettah Public Transport District.

Table 2: Summarizing the critical built environmental conditions.

Street	**Design & Infrastructure**	**Safety & Traffic Cond.**	**Proximity & Land Use**
Olcott Mawatha	Sidewalks are obstructed around Pettah Cross Street Junctions due to economic activities. Ramps should be implemented around access points for transport facilities. Tactile paving is missing. More seating areas and ample shade should be provided.	Heavy traffic volume is present. Traffic control measures are needed. Pedestrian infrastructure like speed bumps and chicanes are not found. No push-button-operated signals and speed tables are present.	More green spaces are needed.
	Good conditions	Average conditions	Good conditions
Street	**Design & Infrastructure**	**Safety & Traffic Cond.**	**Proximity & Land Use**
Railway Station Entry Road	Sidewalks are obstructed by slippery surfaces, garbage, and shopfronts. Crossings and essential pedestrian signals hinder safe walking experience. Existing ramps are poorly designed with slippery and unfinished surfaces. Tactile paving is missing. Poor amenities	Inadequate separation between pedestrian and traffic zones is present. Poor crossing conditions with faded crosswalks are present. Pedestrian infrastructure like speed bumps and chicanes are not found. No push-button-operated signals and speed tables are present.	More green spaces are needed.

	hinder walkability in the major transit hub.		
	Average conditions	Poor conditions	Average conditions
W.E. Bastian Mawatha	Sidewalks are obstructed around railway stations due to commercial activities. The absence of ramps in W.E. Bastian Mawatha poses challenges. Tactile paving is missing.	Traffic control measures are needed. Pedestrian infrastructure like speed bumps and chicanes are not found. No push-button-operated signals and speed tables are present.	None
	Comparatively better conditions	Good conditions	Comparatively better conditions
Saunders Place	Sidewalks are obstructed by light features, uneven surfaces, shopfronts, and trees. Safe crossings and essential pedestrian signals are missing. Ramps should be implemented around access points for transport facilities. Tactile paving is missing. Seating areas and ample shade should be provided.	Inadequate separation between pedestrian and traffic zones is present. Poor crossing conditions with faded crosswalks are present. Pedestrian infrastructure like speed bumps and chicanes are not found. No push-button-operated signals and speed tables are present.	Green spaces are needed.
	Poor conditions	Poor conditions	Average conditions
Bodhiraja Mawatha and other cross-streets	Sidewalks are obstructed entirely by economic activities and shopfronts. Safe crossings and essential pedestrian signals are missing. Ramps should be implemented around access points for transport facilities. Tactile paving is missing. More seating areas and ample shade should be provided. Seating areas and ample shade should be provided.	Extremely inadequate separation between pedestrian and traffic zones is present. Poor crossing conditions with faded crosswalks are present. Pedestrian infrastructure like speed bumps and chicanes are not found. No push-button-operated signals and speed tables are present.	Green spaces are needed.
	Critical conditions	Critical conditions	Average conditions

Good Conditions — Comparatively Better Conditions — Average Conditions — Poor Conditions — Critical Conditions

6. Conclusion

Upon analyzing the findings in alignment with the sustainable city development goals outlined in the GreenSL® Rating System for Sustainable Cities, it becomes evident that there are significant deficiencies in the current state of pedestrian infrastructure, resulting in extremely poor walking conditions. This underscores the urgent need for revitalization and the incorporation of missing elements to cultivate a more sustainable urban environment. The state of sidewalk conditions is of critical importance, as it directly impacts safety, accessibility, and the overall quality of life for pedestrians. Notably, there is a concerning lack of adherence to required physical dimensions. Addressing obstructions arising from unauthorized economic activities calls for robust policy enforcement and relevant regulations to bridge these gaps in pursuit of sustainable city objectives. Urgent attention is also warranted for enhancing pedestrian safety features, a crucial aspect that demands immediate action from relevant authorities. Furthermore, a well-designed public awareness program holds the potential to positively influence environmental conditions and promote responsible pedestrian behavior. It is imperative to emphasize that these efforts must be undertaken while preserving the district's diverse and dynamic land use patterns, which have played a pivotal role in safeguarding the district's vibrancy and are essential in progressing towards a more sustainable urban environment.

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STUDY ON THE EFFECT OF JOINT THICKNESS ON COMPRESSIVE STRENGTH OF BLOCK MASONRY WALLS CONSTRUCTED WITH MANUFACTURED SAND MORTAR

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Abstract: In the construction industry, value engineering and sustainability principles hold significant importance. Investigating viable alternatives during global crises, such as the current situation, is essential. The construction industry in Sri Lanka suffers from a shortage of skilled masons currently, leading to poor workmanship and high material consumption. In this study, the investigation was carried out to study the effect of joint thickness on the compressive strength of block masonry walls using an economical and eco-friendly mortar type. By optimizing the joint thickness, not only it is possible to enhance the quality of the brickwork, but it is also possible to reduce material consumption through sustainable practices. This study thoroughly examines the correlation between the thickness of joints and the compressive strength of masonry walls. Experimental investigations aimed to construct prisms with cement blocks, river sand, and manufactured sand mortar. The experimental results show that masonry with 10 mm thick mortar has a higher strength than that of 15 mm or 20 mm thick mortar joints. The strength of the prism decreases as the joint thickness increases. It is recommended that an ideal joint thickness of 10 mm is suitable for block masonry walls. This study will evaluate the capability of manufactured sand as an alternative for river sand in mortar mix, emphasizing the impact of joint thickness on the compressive strength of masonry walls.

Keywords: Compressive strength; Joint thickness; Sustainability; Manufactured sand; River sand; Masonry prisms

1. Introduction

In today's modern world, value engineering and sustainability are two crucial aspects. In Sri Lanka, there is a lack of skilled masons in the construction industry, leading to poor workmanship in masonry construction. It is important to use the optimum joint thickness in masonry construction to ensure optimal results. The extraction of sand from river basins has caused significant environmental harm, therefore manufactured sand has become a highly favorable option due to its accessibility, ease of extraction, minimal environmental impact, and cost-effectiveness. Using M sand that is processed without any soluble or organic materials can positively impact strength prevent river erosion and mitigate environmental destruction. The study aims to investigate the effect of joint thickness on the compressive strength of masonry walls using an economical and eco-friendly mortar type. Manufactured sand will be used as an alternative to river sand in mortar- mix for masonry. By varying the joint thickness while keeping other parameters constant, the research intends to provide valuable insights into the effect of joint thickness on masonry performance, thereby benefiting the construction industry. In this study, the following tasks were carried out: masonry prisms were constructed in the laboratory for different joint thicknesses using M sand and investigated the compressive strength of masonry prisms, determine the variation of the compressive strength of masonry prisms when using river sand and check the capability of using manufactured sand as an alternative to river sand.

Masonry specimens are divided into three categories: masonry prism, masonry wallet, and masonry wall. Drysdale and Hamid found that a three-course prism represents masonry properties more precisely than a two-course prism. Ganesan and Ramamurthy's findings suggest that the influence of bed mortar type and vertical mortar joint properties on the behavior of prisms is minimal. Hamid suggested that the number of courses should be considered rather than the height-to-thickness (h/t) ratio (Thaickavil & Thomas, 2018). The International One - and Two-Family Dwelling Code (IRC) specifies a maximum joint thickness of 10 mm for masonry bed joints, except the starter course, which may range in thickness from 6 mm to 19 mm when constructed over foundations. (Framing, 2006). Eurocode 6 provides two equations for determining the characteristic compressive strength of masonry, one for thin joints between 0.5 mm and 3 mm and another for a typical mortar joint of 10 mm. (Heuropeannon,2011) Using the damage mechanics inspired modeling method, an equation was derived to describe the relationship between mortar joint thickness and average masonry strength (Zahra & Dhanasekar, 2016). Based on elasticity theory, a mathematical model determines optimal mortar joint thickness in brick-mortar couplet, achieving 10mm thickness (Nwofor & Sule, 2012).

Shrinivasa Rao's study on bed joint thickness and compressive strength in soil cement brick masonry prisms revealed that the ratio of bricks to mortar and elastic modulus affects the strength of the masonry. A brick-to-mortar modulus ratio of more than 1, decreases the compressive strength of masonry (Shrinivasa Rao et al., 1995). The study by Reddy, Lal, and Rao examined the impact of joint thickness on compressive strength and the stress-strain relationship in soil cement masonry prisms (Reddy et al., 2009). It has been suggested that the mortar joint thickness should be maintained within a 7-12 mm range when constructing autoclaved fly ash-lime brick masonry (Tang, 2012). .A. J. Francis, L. E. Jerrems, and C. B. Horman demonstrated that the strength of four-brick prisms decreases as the mortar thickness increases. As the thickness of the joints increases, perforated bricks tend to lose more strength compared to solid bricks (Hendry, 1998). When the mortar joint thickness was reduced from 10 mm to 4 mm, the compressive strength of the masonry prisms increased by 15%. Compared to conventional mortar mix, polymer cement mortar-bedded prisms exhibit greater compressive strength (Thamboo et al., 2013). Brick-masonry samples were tested under compressive stress using non-destructive techniques. Breaking strain, ultrasonic pulse speed, and ultrasonic pulse velocity increased as mortar bed joint thickness decreased (Monteagudo et al., 2011). Li-Guang Xiao and Wen-hao Xing used ANSYS to analyze how mortar thickness affects AAC block compressive strength. According to the study, the masonry's strength decreases when the mortar's thickness increases. (Xiao & Xing, 2020) Finite element analysis using LUSAS software revealed that minimizing mortar joint thickness enhances overall compressive strength in masonry (Bakhteri et al., 2004).

2. Methodology

To achieve the objectives of this study, a methodical experimental approach was used. Using standardized materials and construction techniques, masonry prisms were constructed with varying joint thicknesses. Compressive strength tests were performed on these samples, and their analysis was conducted to determine how joint thickness affects the performance of masonry.

2.1 Flow chart of the methodology

Figure 1 shows the flow chart of the methodology.

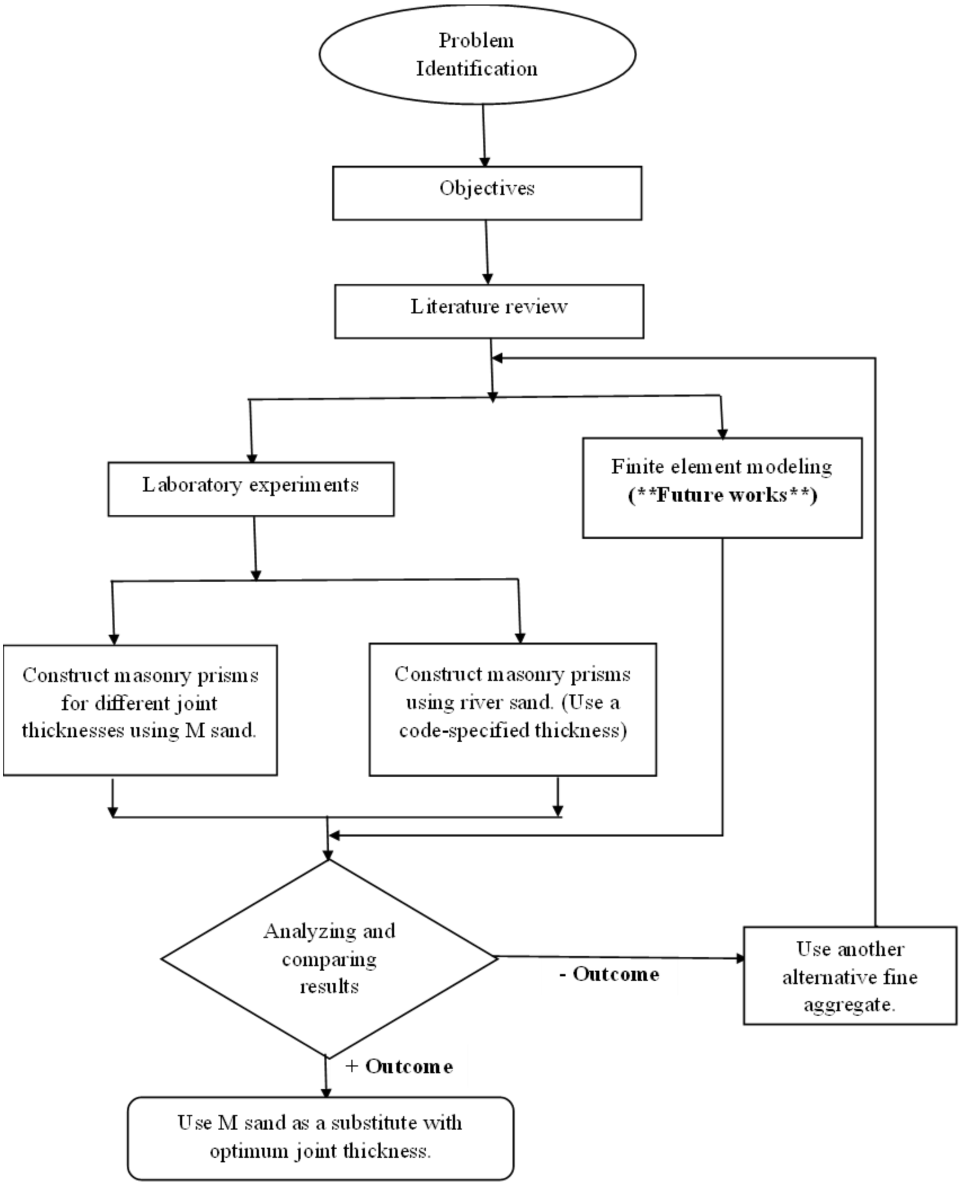

Figure 1: Flow chart of the methodology.

2.2 Materials and mix proportion

2.2.1 Cement blocks

Cement blocks are available in solid, cellular, and hollow varieties. SLS 855 specifies that the normal range for block density is between 1000kg/m^3 and 2800kg/m^3, and the minimum optimum strength of the cement sand block should be 2.5 N/mm^2 (Savitha, 2012). For this study, 356 mm x 178 mm x 102 mm solid cement blocks were used.

2.2.2 Cement and fine aggregate

Locally available manufactured sand and river sand are used for mortar mixes as fine aggregate. Sand that passes in a 2.36mm sieve (Medium sand) has been used. Ordinary Portland Cement (OPC) which is specified by SLS 107:2015 Strength Class 42.5 R used for cement(Priyadarshana et al., 2013).

2.2.3 Mix proportion

Mortar was prepared by thoroughly blending the constituent materials (cement, sand, water) according to the specified proportions, to achieve a uniform mortar mix. Both mortar mixes were prepared with a water-to-cement ratio of 0.8 by mass and a cement-to-sand ratio of 1:5 by volume.

2.3 Experimental work

2.3.1 Construction of masonry prisms

Cement blocks were used to build masonry prisms. The construction of the masonry prisms followed the guidelines outlined in ASTM C1314(ASTM International, 2015). For the manufactured sand mortar mix, mortar thicknesses of 10mm, 15mm, and 20mm were used, whereas a thickness of 10mm was used for the river sand mortar mix. For each mortar's thickness, three masonry prisms were constructed, resulting in a total of 12 prisms for this study. After construction, each prism was securely sealed using a thick polythene cover to protect the prisms and keep each prism where the temperature is kept at (24 ± 8° C) for complete curing before testing. The masonry prisms constructed for this study are shown in Figure 2.

Figure 2: Masonry prisms.

2.3.2 Casting mortar cubes

The guidelines described in the Indian Standard (IS) 2250 code used for casting mortar cubes(Version et al., 2009). To determine the compressive strength of mortar, mortar molds with dimensions of 70.6 mm x 70.6 mm x 70.6 mm were used. Three mortar cubes were prepared for each river sand and manufactured sand mortar mixes. The demoulding process was completed after 24 hours, and the cubes were kept in the water tank for 28 days for curing. Figure 3 shows the mortar cubes cast for this study.

Figure 3: Casting mortar cubes.

2.3.3 Compressive strength of cement blocks

The cement blocks used for the experiment had gained 28-day compressive strength. Using measuring tape, determine the length and width of the solid blocks. The compressive strength of the cement blocks was determined using the Universal Testing Machine (UTM). For reliable results, three cement blocks were tested for compressive strength, and determined the average compressive strength.

2.3.4 Compressive strength of mortar cubes

After 28 days, the mortar cubes were removed from the curing tank. The cubes were then placed on the UTM, and the length and width of the mortar cube were measured before loading. Applied the force at a uniform rate until the cube fractures. Recorded the maximum load applied to the cube. Figure 4 shows the crushing mortar cubes using the universal testing machine.

Figure 4: Crushing mortar cubes using a universal testing machine (UTM).

2.3.5 Compressive strength of masonry prisms

Figure 5: Loading prisms by AMSLER testing machine.

In ASTM C1314 (ASTM International, 2015), correction factors are specified for prisms with different aspect ratios. This is because the ratio of height to the least lateral dimension (h_p/t_p) of the prism has a notable effect on the compressive strength of the masonry prism. The height and thickness of masonry prisms were measured before loading the prisms to calculate the correction factors. The prisms were loaded in the AMSLER Testing Machine (see Figure 5). The load was uniformly distributed throughout the prism's top surfaces. The maximum load was recorded when the prism failed.

3. Results and analysis

The results of the tests conducted on the cement blocks, mortar cubes, and masonry prisms were analyzed in this study.

3.1 Compressive strength of cement block

The compressive strengths of solid blocks are tabulated in Table 1.

Table 1: Compressive strength of cement block

Specimen	Compressive Strength (N/mm^2)	Average Compressive Strength (N/mm^2)
Block 1	6.69	6.31
Block 2	6.35	
Block 3	5.87	

3.2 Compressive strength of mortar cubes

The compressive strengths of mortar cubes are tabulated in Table 2 (RS 1- River Sand mortar cube 1; MS 1 - M sand mortar cube 1). Table 3 gives the correction factors specified in ASTM1314.

Table 2: Compressive strength of mortar cubes

Specimen 1:5 Mortar mix	Compressive Strength (N/mm^2)	Average Compressive Strength (N/mm^2)
RS 1	7.10	9.63
RS 2	10.91	
RS 3	10.89	
MS 1	20.00	17.30
MS 2	16.55	
MS 3	15.37	

Table 3: Correction factors of ASTM1314

h_p/t_p	1.3	1.5	2.0	2.5	3.0	4.0	5.0
Correction factor	0.75	0.86	1.0	1.04	1.07	1.15	1.22

3.3 Compressive strength of masonry prisms

The compressive strengths of masonry prisms are tabulated in Table 4 (RS10 - River Sand 10 mm mortar thickness masonry prism; MS10 - Manufactured Sand 10mm mortar thickness masonry prism).

Table 4: Compressive strength of masonry prisms

Specimen	Correction Factor	Corrected Compressive Strength (N/mm^2)	Average Compressive Strength (N/mm^2)
RS10 (1)	1.118	4.51	4.49
RS10 (2)	1.118	4.32	
RS10 (3)	1.118	4.63	
MS10(1)	1.118	4.15	4.06
MS10(2)	1.118	4.34	
MS10(3)	1.118	3.68	
MS15(1)	1.122	3.57	3.45
MS15(2)	1.122	3.75	
MS15(3)	1.122	3.03	
MS20(1)	1.126	3.06	2.93
MS20(2)	1.126	3.00	
MS20(3)	1.126	2.73	

3.4 Comparison of results

Figure 6 compares the compressive strength of masonry prisms constructed using manufactured sand mortar with different joint thicknesses.

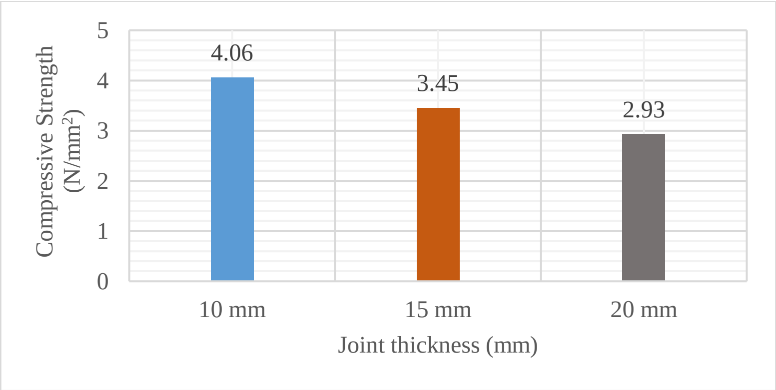

Figure 6: Compressive strength of manufactured sand prisms with different joint thicknesses.

Figure 7 compares the compressive strength of masonry prisms constructed using M sand and river sand mortar (Only for 10mm mortar joint thickness).

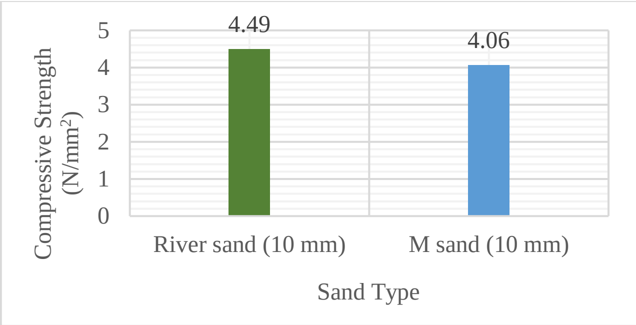

Figure 7: Compressive strength of prisms (10mm mortar joint thickness).

Table 4 indicates the compressive strength of the masonry prism after 28 days for various mortar thicknesses of 10mm, 15mm, and 20mm, respectively. For the experiment, Group 1 cement blocks were used, and the general mortar was used for binding, according to Table 3.3 in Eurocode 6. As a result, the value of K is 0.55.

$$f_k = K f_b^{\alpha} f_m^{\beta} \text{ ; } (\alpha = 0.7, \beta = 0.3) \tag{1}$$

f_k - Characteristic compressive strength of masonry
f_b - Compressive strength of block
f_m - Compressive strength of mortar

According to Eurocode, a joint thickness of 10mm is recommended. The characteristic compressive strength of the masonry prism is determined using river sand mortar, as specified by equation 1.

$$f_k = K f_b^{\alpha} f_m^{\beta} \text{ ; } \quad (f_b = 6.31\ Nmm^2,\ f_m = 9.63\ Nmm^2)$$
$$f_k = 0.55\ x\ f_b^{\alpha}\ x\ f_m^{\beta}$$
$$= 0.55 \text{ x } 6.31^{0.7} \text{ x } 9.63^{0.3}$$
$$= 3.94 \text{ N/mm}^2$$

The characteristic compressive strength of the masonry prism, built using manufactured sand mortar, can be determined by equation 1.

$$f_k = K f_b^{\alpha} f_m^{\beta} \text{ ; } \quad (f_b = 6.31\ Nmm^2,\ f_m = 17.30\ Nmm^2)$$
$$f_k = 0.55\ x\ f_b^{\alpha}\ x\ f_m^{\beta}$$
$$= 0.55 \text{ x } 6.31^{0.7} \text{ x } 17.30^{0.3}$$
$$= 4.70 \text{ N/mm}^2$$

Deviations from the expected values according to Eurocode and experimental values are tabulated in Table 5.

Table 5: Comparison between expected value and experimental value

Specimen (Prism)	The expected characteristic compressive strength (N/mm²)	Experimental value (N/mm²)	Deviation (%)
RS 10mm	3.94	4.49	13.95
MS 10mm	4.70	4.06	13.61
MS 15mm	-	3.45	-
MS 20mm	-	2.93	-

3.5 Mode of failure

Vertical cracks were found to be the cause of the failure of masonry in all specimens. These cracks first appeared at the mortar joint when the load was applied and then extended upwards and downwards, resulting in splitting fractures. On rare occasions, inclined cracks were observed in the middle of the specimen, and a crack was generated from the top of the prism or sometimes from the bottom of the prism. This could be due to the friction between the plates and specimen. Prisms typically fail due to the development of vertical cracks along their height, which may have been caused by the lateral expansion of the mortar.

Figure 8: Vertical cracks.

4. Discussion

Masonry prisms with a mortar thickness of 10mm showed 13.95%, and 13.61% deviations from the expected f_{ck} values when tested with both river sand and manufactured sand respectively. The compressive strength of prisms with the 10mm mortar thickness which is produced using manufactured sand decreased by 9.57% compared to the experimental value of the river sand masonry prisms due to the inherent characteristics of manufactured sand. River sand is composed of naturally rounded particles that interlock more effectively, resulting in better load transfer and increased compressive strength. The compressive strength of manufactured sand mortar cubes is almost twice that of river sand mortar cubes. Still, the compressive strength of masonry prisms made with these mortar types exhibits minimal disparity. The experimental results demonstrate that the expected characteristic compressive strength, as specified in the Eurocode, is significantly different for masonry prisms constructed with 15mm and 20mm mortar joint thicknesses. Based on conventional mortars, it has been determined that a joint thickness of 10mm is the most appropriate for masonry. The study found that the strength of mortar variations has a negligible impact on the maximum load a prism can withstand. It is important to acknowledge that the thickness of the joint can significantly influence the compressive strength, as when the mortar's thickness increases, the masonry's compressive strength decreases, and it becomes more noticeable beyond 10 mm.

5. Conclusion

This study investigates the thickness of masonry joints. The intention is to have a deeper understanding of the implications through examination and analysis. The results and conclusions will add to the body of knowledge in this field. The preliminary observations and conclusions of this study are: The Eurocode's equation for determining the characteristic compressive strength is more accurate when applied to mortar thicknesses of 10 mm; In this test, the cement blocks are not completely soaked in water. Therefore, the inside of the block is unsaturated by water. This may cause the rate of water penetration into the block through the M sand mortar layer to be higher than that of the river sand mortar layer. This leads to a reduction in the bond strength of the mortar layer due to the insufficient amount of water requirement in the M sand masonry prisms; a Masonry prism with a thickness of 10 mm has a higher compressive strength than a masonry prism with a thickness of 15 mm or 20 mm. The compressive strength of masonry decreases as joint thickness increases; An ideal joint thickness of 10 mm is recommended when manufactured sand is used for masonry building; Based on the findings, it has been found that the joint thickness influences the strength of the masonry prism; The deviation between expected and obtained experimental results was around 13% for 10 mm. Therefore, it is better to do this practical work using 3-course prisms or masonry wallets to understand masonry behavior. For future works, finite element analysis can be carried out using ABACUS / ANSYS to study the joint thickness's effect on masonry's compressive strength. To ensure precise outcomes, expanding the experimental sample size might be required.

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A STUDY ON THE SENSE OF COMMUNITY AND BEHAVIOUR PATTERNS OF INHABITANTS IN NUGEGODA COMMERCIAL STREETS

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Abstract: Nugegoda is a rapidly urbanized and vibrant mixed-use city that offers a diverse range of goods, services, and public facilities. The research problem that motivates this study is the impact of commercial development along the main street, on the sense of community in the area, as well as the lack of gathering spaces within the area that further intensifies this issue. The study focused on how the built environment impacts the formation of a sense of community and human behavior patterns. Through observational data collection and thematic analysis, the study revealed insights into the community dynamics of three selected spots that have developed a sense of community within the built environment of the street itself. The study reveals insights into the temporal nature of the area and the types of activities that occur during specific times, highlighting the importance of understanding these factors to better plan and design for the community. Additionally, the study identifies the impact of specific built environments on attracting inhabitants and enhancing their interaction and consequentially the quality of urban life. The study provides valuable insights into the challenges and opportunities for creating a sense of community in commercial streets and highlights the need for a well-planned built environment to enhance positive social interactions among inhabitants.

Keywords: Mixed-use; Sense of community; Built environment; Temporal nature; Human behavior patterns

1. Introduction

Human beings are social animals, and they thrive on social connections and interactions. Human behavior patterns are heavily influenced by the sense of community, which refers to the feeling of belonging and connectedness to a group of people who share similar values, norms, and goals. The sense of community is crucial to people's mental and emotional well-being, and it plays a vital role in shaping their behaviors, attitudes, and values.

The sense of community is an essential component of place-making. It is critical to create vibrant, liveable, and sustainable urban environments that support the well-being and quality of life of their inhabitants. Understanding the role that the sense of community plays in shaping the behavior patterns and satisfaction of inhabitants is essential for people who are looking to create a more cohesive, equitable, and sustainable community. This study focuses on the commercial streets of Nugegoda, Sri Lanka, a vibrant area known for its markets, shops, institutions, and transit systems. The research aims to investigate the sense of community and behavior patterns of inhabitants in Nugegoda's commercial streets, with a focus on the built environment.

1.1 Research Background.

Nugegoda is a vibrant city known for its bustling markets, shops, and educational institutions, attracting both locals and tourists. (Kuruppu,2017). In Nugegoda, while the overall city offers a good quality of life, its highly active commercial town center lacks a dedicated community gathering place. The rapid development of businesses along the main road has led to a fragmented community, with a transient population that hinders a sense of belonging and connection. Commercial spaces like cafes and restaurants, while available, prioritize efficiency over community building. The focus on commerce has also resulted in increased traffic and congestion, discouraging community engagement.

However, even with the fewer spaces for gatherings people often find a creative way to find a sense of community in Nugegoda Streets such as under the shades of trees, bus halts, urban pockets, street ends, etc. These informal spaces can be just as important to community building, and they often reflect the unique character and identity of the local community.

1.2 Research Questions

- What is the concept of a sense of community and how does it apply to the inhabitants of Nugegoda commercial streets?
- What factors contribute to the development of a sense of community in Nugegoda streets?
- How does the built environment shape the sense of community and behavior patterns in Nugegoda streets?

1.3 Research objectives

- To explore the concept of a sense of community among inhabitants in Nugegoda commercial streets.
- To Understand the types of inhabitants and their behavior patterns in Nugegoda Street.
- To identify the factors that contribute to the development of a sense of community in Nugegoda commercial streets.
- To investigate the role of the built environment in shaping the sense of community and behavior patterns in Nugegoda commercial streets.

2. Theoretical Base

2.1 Theory of Sense of Community

McMillan and Chavis, in their article "Sense of Community: A Definition and Theory" published in the Journal of Community Psychology in 1986, developed the concept of sense of community and identified four key elements that contribute to it. These four elements can be seen as the foundational components of a sense of community.

1. Membership: feeling a sense of belonging and connection to a community.
2. Influence: having the ability to contribute to and shape the community.
3. Integration and fulfillment of needs: satisfying social and psychological needs through participation in the community.
4. Shared emotional connection: feeling an attachment and emotional connection to the community and its members.

Overall, the four components of a sense of community developed by McMillan and Chavis (1986) highlight the importance of social connection, participation, and shared identity in creating a strong sense of community. By promoting membership, influence, integration, fulfillment of needs, and shared emotional connection, communities can create a sense of belonging and social cohesion that supports the well-being and success of its members.

2.3 Components of Sense of Community in Place-Making

It can be said that urban planners and designers, in general, have adopted the four components of a sense of community to place-making. However, it's important to note that over time, other researchers, and theorists have expanded upon and refined these components, adding new ones such as physical environment and local identity, to create a more comprehensive understanding of the sense of community in place-making.

The components of a sense of community in place-making include:

i. **Physical Environment:** Design elements such as lighting, seating, landscaping, and layout contribute to comfort, safety, and social interaction in public spaces (Gehl, 2010; Pretty & Thompson, 2006).

ii. **Social Interaction:** Encouraging social interaction through seating arrangements, events, and shared experiences is crucial for community-building (Carmona et al., 2010).

iii. **Local Identity:** Public spaces should reflect the community's history, culture, and values, utilizing elements like art, landmarks, and local materials to create a unique sense of place (Sadler & Gill, 2019; Zhang et al., 2017).

iv. **Accessibility and Connectivity:** Ensuring accessibility and connectivity within public spaces, through features like accessible paths and facilities, promotes inclusivity (Gehl, 2010; Kaufman & Riverson, 2015).

v. **Sense of Ownership:** Involving the community in design, programming, and maintenance fosters a sense of ownership and investment (Carmona et al., 2010).

vi. **Safety and Security:** Incorporating design elements like lighting and landscaping enhances safety and security, enabling community development (Purcell et al., 2019).

vii. **Diversity and Inclusivity:** Celebrating the diversity of the community through public art and cultural events contributes to inclusivity (Sadler & Gill, 2019; Staats & Griesinger, 2020).

viii. Overall, the components of a sense of community in place-making are focused on creating public spaces that are attractive, functional, and meaningful to the people who use them, and that foster a sense of belonging and social connectedness. These components work together to create public spaces that foster a sense of community and support the well-being of individuals within a community.

2.4 Human Behaviour Patterns in the Built Environment

"Human behavior patterns are the habitual ways in which people respond to certain situations, stimuli, or contexts. These patterns can be conscious or unconscious, intentional or unintentional, and can be influenced by individual, social, and environmental factors." (Wendel, 2013).

The built environment is one of the key factors that shape human behavior patterns (Moore,1979)(Figure 1).

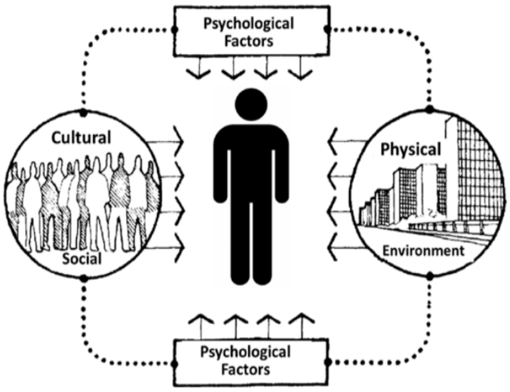


Figure 1: Factors contributing to the sense of community.

The built environment includes the physical infrastructure, buildings, public spaces, transportation systems, and other constructed elements that make up the urban or rural environment (Figure 2).

Figure 2: Building Edges impact on human behavior patterns in streets.

Understanding the diversity of inhabitants and their behavior patterns is essential for creating a sense of community within a place (Staats et al, 2004). It's a complex and multifaceted factor that can be influenced by a wide range of factors, including social norms, physical environment, and individual preferences (Figure 3).

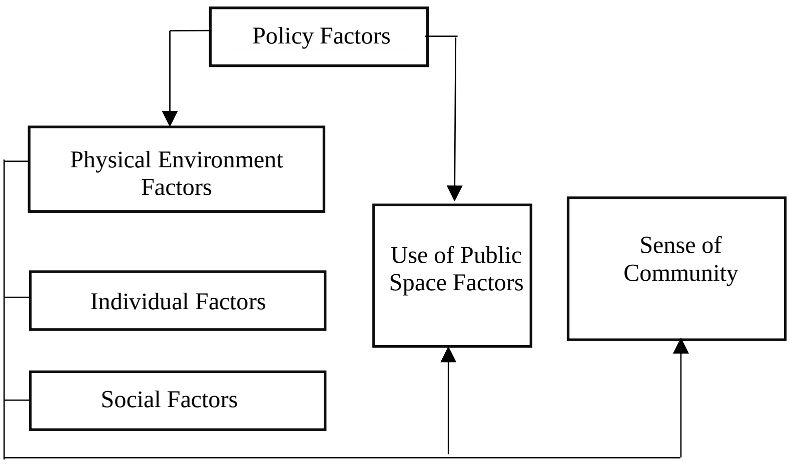


Figure 3: Factors contributing to the sense of community.

Creating spaces that support positive behavior patterns can lead to numerous benefits for inhabitants (Lynch,1960). For example, designing pedestrian-friendly streets and public spaces can encourage physical activity and promote a sense of community. Conversely, spaces that promote negative behavior patterns, such as unsafe or unclean environments, can create feelings of insecurity and decrease inhabitants' sense of ownership and connection to the community.

Modifying inhabitants' behavior patterns can be achieved through place-making strategies that promote positive behaviors (Gehl,2010). For example, designing public spaces that encourage social interactions, such as playgrounds or community gardens, can encourage a sense of community ownership and increase social capital. Additionally, creating spaces that support healthy behaviors, such as installing bike lanes or walkways, can promote physical activity and reduce reliance on cars.

1.5 Research Method

This study employs a qualitative research design based on the observational method to explore human behavior and a sense of community in Nugegoda streets. The research will involve observing three selected spots in Nugegoda streets (Figure 4), which have a sense of community to some extent.

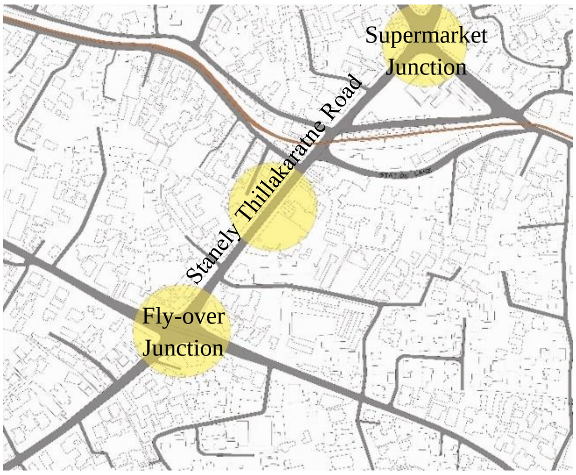


Figure 4: Selected location in Nugegoda commercial streets.

These spots were identified based on their popularity among residents and their potential to provide insights into the community dynamics in the area.

The observation will be conducted at three different times of the day over three days, including a weekday (Monday to Friday), Saturday, and Sunday. The selected times were morning (7-10 am), afternoon (12-3 pm), and evening (5-8 pm), to capture variations in community activities and behavior throughout the day. The observations will be conducted by the researcher in person, using a notebook and pen to record field notes. The Primary data collected through observation will be analyzed using thematic analysis and illustrations to identify patterns and themes in human behavior and community dynamics. The choice of qualitative research design and observational method is appropriate for this study as it allows for an in-depth exploration of the research question and provides insights into the social and cultural context of the research site.

As for secondary data, a two-stage approach was adopted. In the first stage, data was collected by analyzing relevant articles, research papers, and books. In the second stage, the analysis of a case study that was similar in context to Nugegoda was undertaken.

3 Research and analysis.

3.2. Nugegoda Flyover Junction

3.2.1. Physical / Built Environment of Nugegoda Flyover Junction

Nugegoda Flyover Junction a is busy and dynamic urban space with a complex physical environment. It connects High-Level Road, Stanley Thilakaratne Mawatha, and S. De S Mawatha and is a bustling hub of commercial and transportation activities (Figure 5).

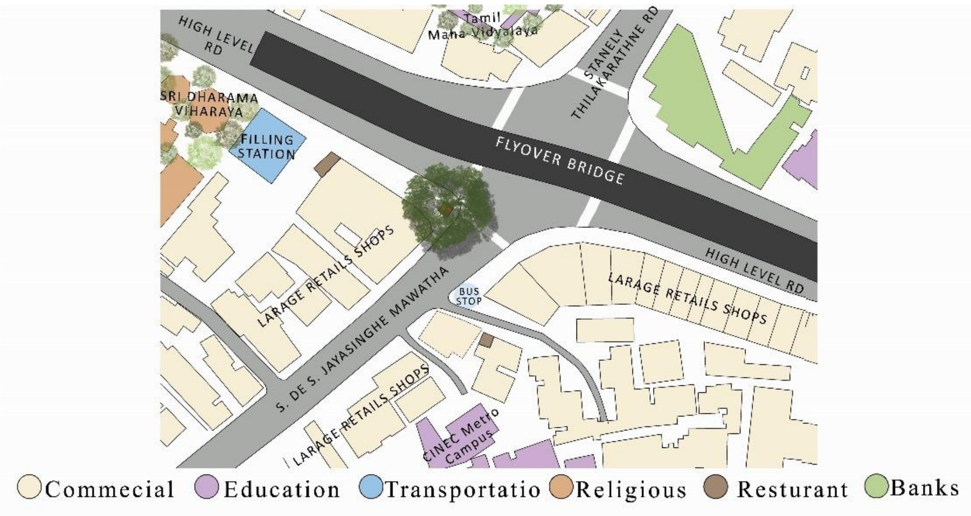


Figure 5: Layout of Nugegoda Flyover Junction.

One of the most prominent features of the junction is its flyover structure, which spans over the intersection and provides an efficient link between High-Level roads. Still, the area is characterized by heavy vehicular traffic during peak hours (Figure 12). In addition to the flyover, the buildings in the area are primarily commercial, with a mix of small shops and larger retail stores. The Junction is home to several shopping malls, including Nolimit, Fashion Bug, Manjari, and Cool Planet etc (Figure 6). Another notable feature of the Nugegoda Flyover Junction is the large Bo Tree that stands beneath the center of the junction, providing a natural focal point and shade for pedestrians and visitors alike. The Bo tree is considered sacred by many Sri Lankans and is an important cultural symbol in the country (Figure 6).

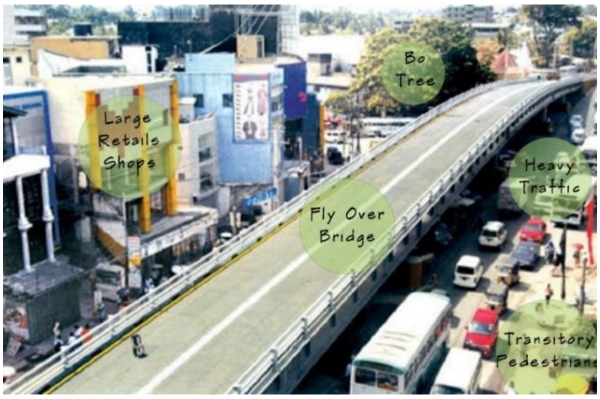


Figure 6: Built environment of Nugegoda Flyover Junction.

The sidewalks in the area are relatively wide, allowing for a significant amount of pedestrian traffic. The area is generally well-lit at night, with streetlights and signage providing a bright and vibrant atmosphere. Despite the busy nature of the space, the physical environment is generally well-maintained, with regular cleaning and maintenance carried out by local authorities.

3.2.2 Human Behaviour Pattern of Flyover Junction

The survey was carried out during weekdays (Figure 7), and weekends (Figure 8).

<u>Weekdays</u>:

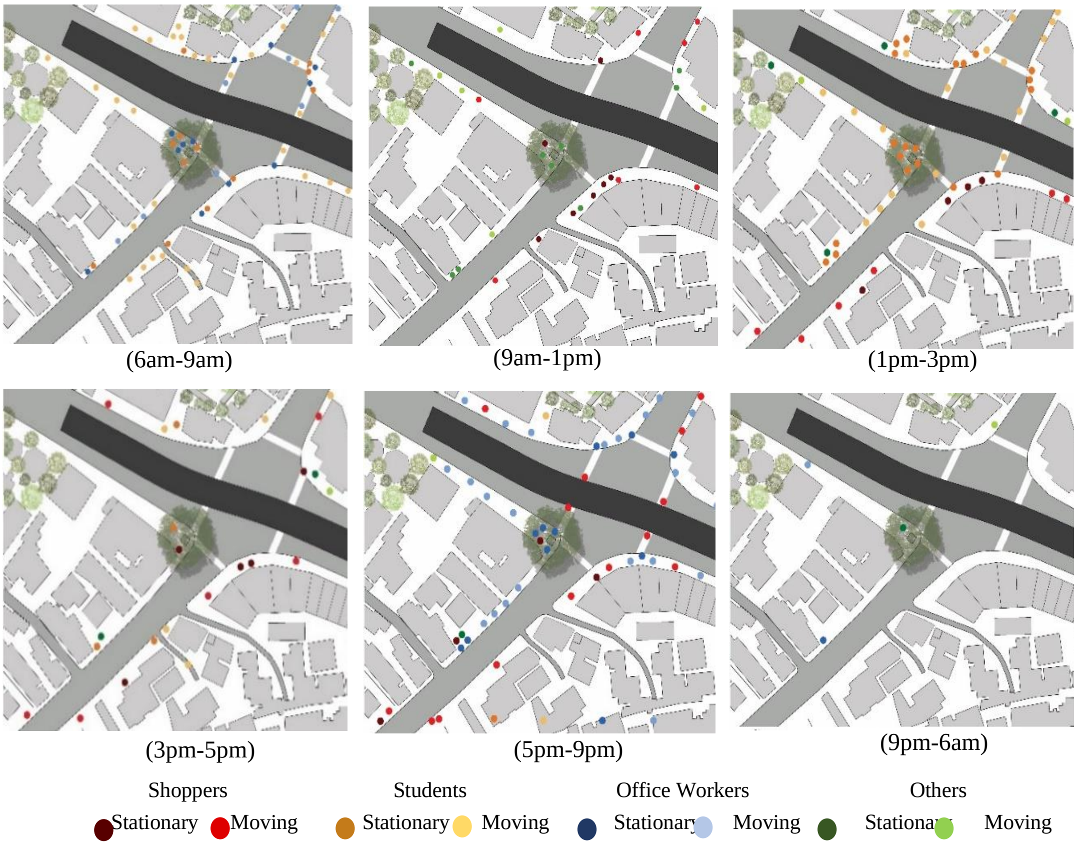


Figure 7: Behaviour map on weekdays.

Weekends:

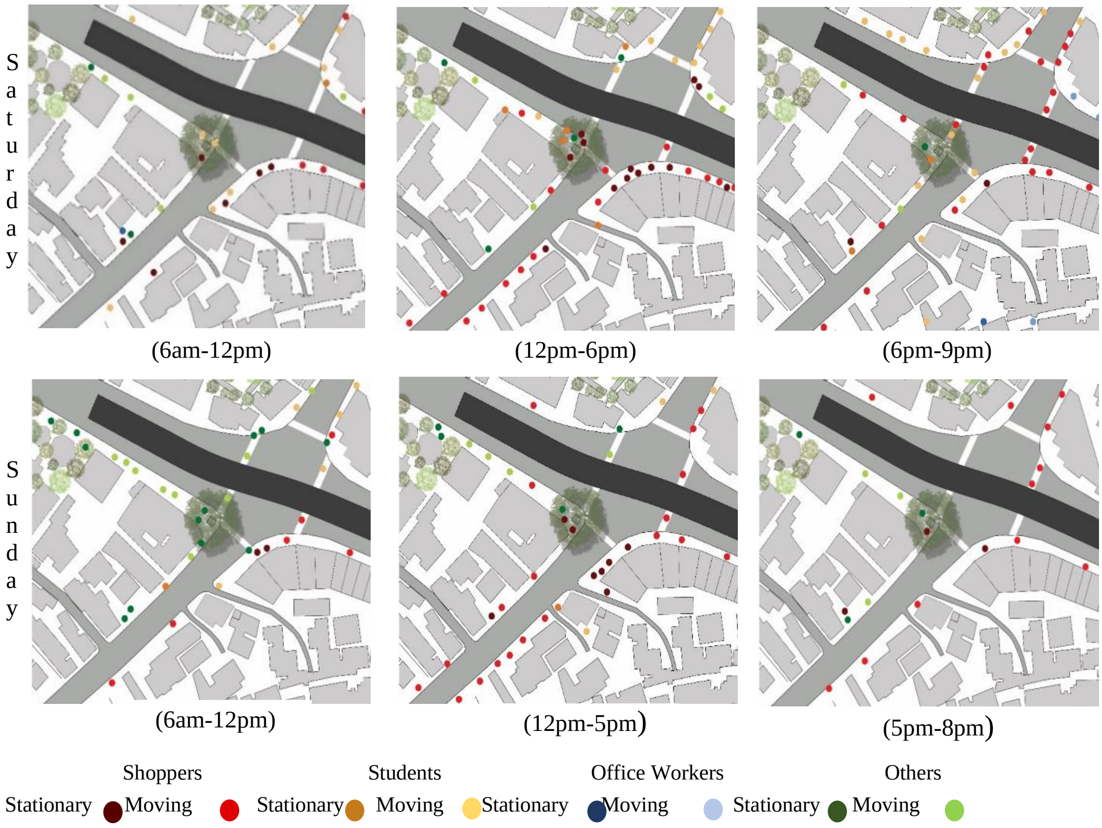


Figure 8: Behaviour map on weekends.

3.2.2 Sense of Community

Nugegoda Flyover Junction is a lively area that is frequented by a diverse range of people throughout the day, including shoppers, students from nearby institutes and schools, workers, and others. Despite the absence of a formal community structure, the physical environment of the area plays a significant role in fostering a sense of community among its transitory population (Figure 9).

Figure 9: Cross section of Nugegoda Flyover Junction.

The shade of the Bo tree and the relatively wide pedestrian walkways provide a space for people to gather and socialize, making it an ideal location for transitory populations. People passing through the area often take a break and relax under the shade of the tree, creating a sense of connection and community among strangers (Figure 10).

Figure 10: Sense of community under the Bo tree.

Figure 11: Sense of community under the Bo tree.

Similarly, the wide entranceway of the Nolimit building creates a welcoming atmosphere, and people often congregate there to chat or take a break while waiting for their vehicle, further enhancing the sense of community in the area (Figure 11).

3.3 Nugegoda Super Market Junction

3.3.1 Physical / Built Environment Nugegoda Super Market Junction

The Nugegoda Super Market Junction is a busy urban area that connects several major roads, including Nawala Road, Stanley Thilakaratne Mawatha, and Old Kasbewa. The physical environment of the area is shaped by a mix of commercial buildings, public transportation infrastructure, and natural vegetation (Figure 12).

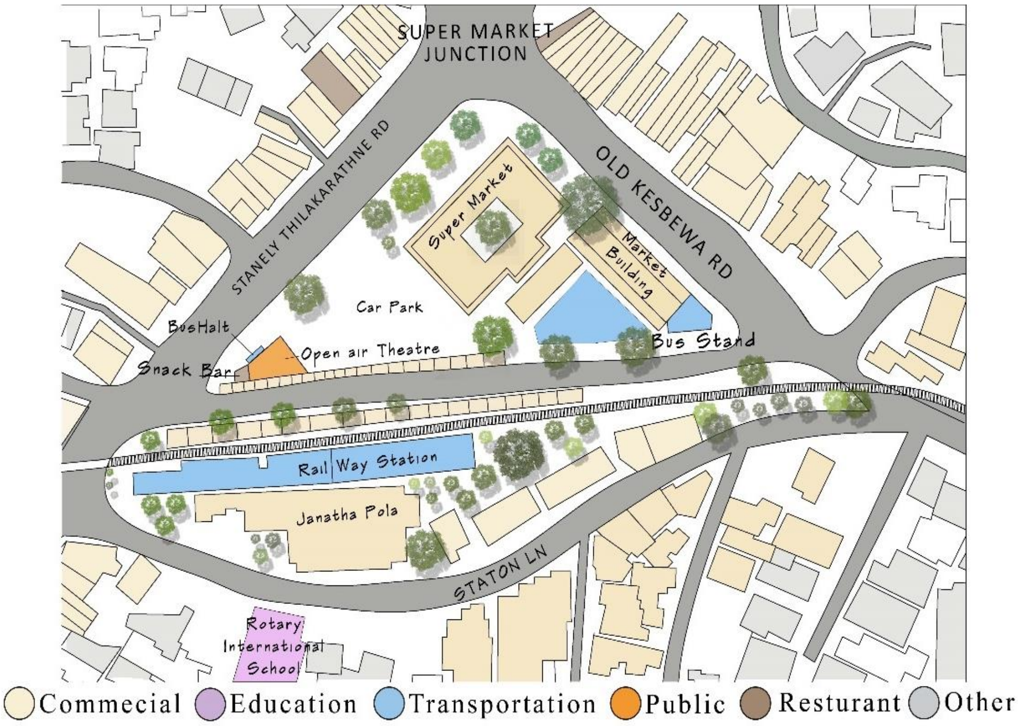


Figure 12: Layout of Nugegoda Supermarket.

a b c

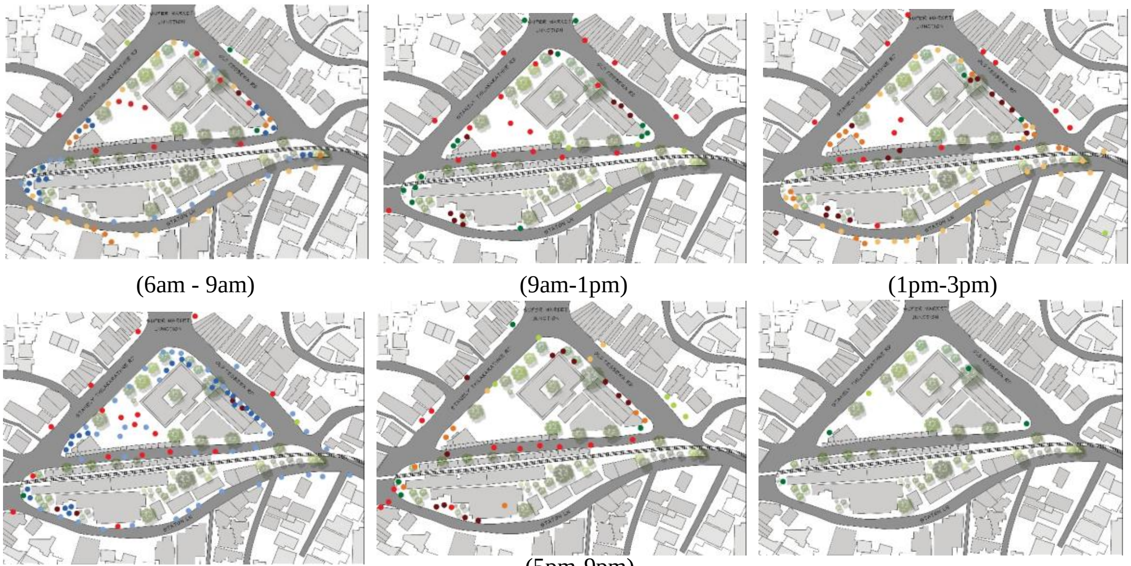
Figure13: (a) Supermarket (b) Open-air market (c) Railway station

One of the most prominent features of the junction is the Supermarket building, which is a large commercial complex with a spacious car park surrounding it. Despite the supermarket not functioning as much, the car park serves as the main parking area for the entire junction, making it a popular spot for commuters and shoppers alike (Figure 13. a). The open-air market with the Large Nuga tree in the area is another significant feature of the junction's physical environment. The market is characterized by vendors' stalls arranged in rows along the streets (Figure 13. b). The junction is also home to a railway station and bus stand which is situated near the Supermarket building, making it easily accessible for commuters (Figure 13. c).

3.3.2 Human Behaviour Pattern of Nugegoda Super Market Junction

The survey was carried out during weekdays (Figure 16), and weekends (Figure 17).

Weekday:



(6am - 9am) (9am-1pm) (1pm-3pm)

(3pm-5pm) (5pm-9pm) (9pm-6am)

Shoppers: Stationary, Moving | Students: Stationary, Moving | Office Workers: Stationary, Moving | Others: Stationary, Moving

Figure 16: Behaviour map on weekends.

Weekend:

(6am – 12pm) (12pm-5pm) (5pm - 9pm)

Shoppers: Stationary, Moving | Students: Stationary, Moving | Office Workers: Stationary, Moving | Others: Stationary, Moving

Figure 17: Behaviour map on weekends.

3.3.2 Sense of Community

The Nugegoda Supermarket Junction is a bustling hub of activity, with different types of inhabitants gathering in various areas throughout the day. The bus stand and station lane are particularly busy during peak commute hours, with office workers and school students rushing to catch their trains and buses. The open-air market is another popular spot, with shoppers milling about and vendors calling out their wares.

Figure 18: Cross section of Nugegoda supermarket junction (Snack Bar).

Figure 19: Snack bar.

Despite the frenetic pace of activity, the small snack bar located near the bus halt and open-air theatre seems to attract people from all walks of life (Figure 18). This is partly because the snack bar has relatively wide pedestrian pavement, which encourages people to stop and linger for a moment (Figure 19).

3.4 Nugegoda Stanley Thilakaratne Mawatha (In-between Supermarket Junction and Fly-over Junction)

3.4.1 Physical / Built Environment of Nugegoda Stanley Thilakaratne Mawatha

Stanley Thilakaratne Mawatha is an approximately 1.2 kilometers long and relatively wide road that also connects Nugegoda Junction with Flyover Junction (Figure 20).

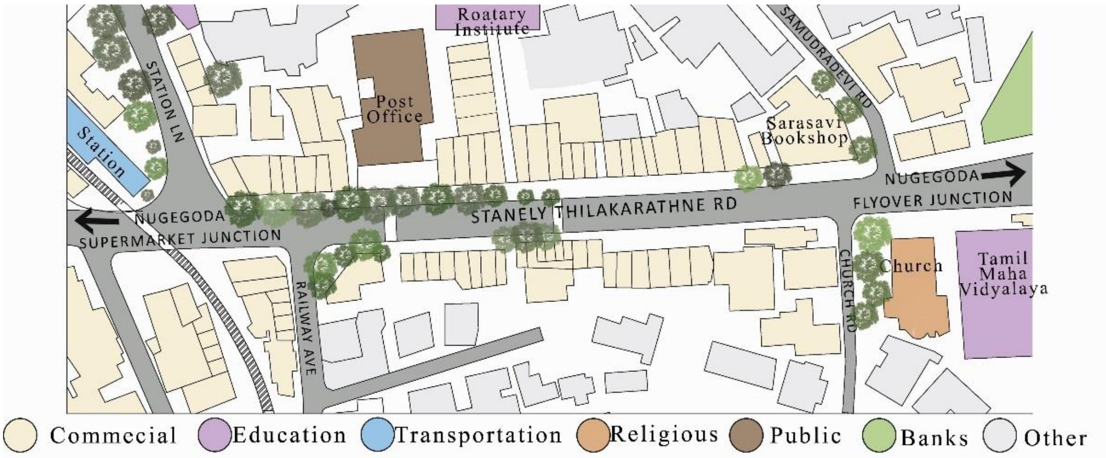


Figure 20: Layout of the Stanley Thilakaratne Mawatha.

The road has a well-maintained pedestrian walkway on both sides of the street. The pedestrian walkway is relatively spacious (2-3m in width) and is equipped with handrails, making it easy and safe for pedestrians to walk along the road.

Figure 21: Tree canopy

Figure 22: Vendors in front of the Post office.

One of the notable features of Stanley Thilakaratne Mawatha is the tree canopy that lines both sides of the street for approximately over 100 meters. These trees provide a shady environment for pedestrians and the small retail shops and vendor shops that are located along the street. The tree canopy not only adds to the aesthetic appeal of the street but also provides a cool and comfortable environment for shoppers and pedestrians, even during hot and humid weather conditions (Figure 21). The street is mostly populated with small retail shops and vendor shops that sell a variety of goods, including clothing, footwear, electronics, and household items. One of the major highlights of the road is the Sarasavi Bookshop, which is one of the largest bookstores in Sri Lanka. The post office located on the road is also a notable landmark in the area (Figure 22).

3.4.2 Human Behaviour Pattern of Nugegoda Stanley Thilakaratne Mawatha

The survey was carried out during weekdays (Figure 23), and weekends (Figure 24).

<u>Weekdays:</u>

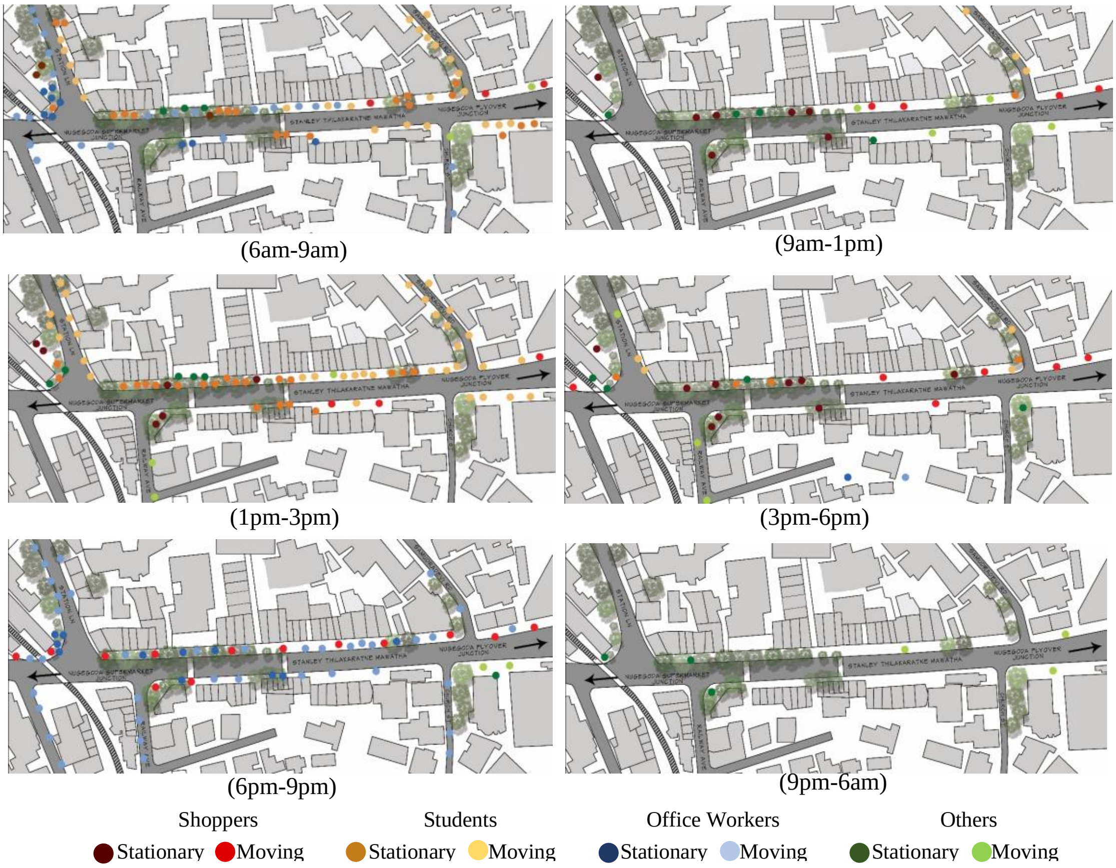


Figure 23: Behaviour map on weekdays.

Weekend:

(6am-12pm)

(12pm-5pm)

(5pm – 9pm)

Shoppers: Stationary, Moving
Students: Stationary, Moving
Office Workers: Stationary, Moving
Others: Stationary, Moving

Figure 24: Behaviour map on weekends.

3.4.3 Sense of Community

Stanley Thilakaratne Mawatha is not just a street connecting two busy junctions, but it also serves as a space that creates a sense of community among the people who use it (Figure 25).

Figure 25: Cross section of Stanley Thilakaratne Mawatha.

Wide pedestrian walkways made the transitory more comfortable to move around. The spacious walkways equipped with handrails and tree shades make all types of inhabitants, including the elderly and children, feel safe to stop and take a break. People tend to slow down their pace while walking through the area, creating a relaxed and friendly environment.

The shady street also serves as a waiting area for people until their companions arrive, even making an ideal spot for chatting with each other (Figure 26).

Figure 25: People having chats and waiting under the trees.

The community feel of the street is further enhanced by the small retail shops and vendor stalls that line the road. The vendors and shopkeepers are familiar faces to the regular visitors, creating a sense of belonging and familiarity (Figure 27).

Figure 26: Vendors stall in the wide pedestrian.

In addition, students and workers can often be seen running errands during peak hours, adding to the liveliness of the street. People who come to Flyover Junction for shopping often park their vehicles at Super Market Junction and walk towards Flyover Junction. Overall, the built environment of Stanley Thilakaratne Mawatha serves as a space that connects people from different walks of life and creates a sense of community, making it a popular spot for socializing and running errands.

Conclusion

This study aimed to explore the sense of community and human behavior in Nugegoda commercial streets using qualitative research methods. The study uncovered the impact of commercial development along the busy street on the sense of community in the area. The high traffic of the transitory population due to the commercial activity along the streets has created a challenge for the development of a sense of community. Furthermore, the lack of gathering spaces within the area has further intensified this issue. Through observational data collection and thematic analysis, the study revealed insights into the community dynamics of three selected spots in the area that have developed a sense of community within the built environment of the street itself.

The study revealed that the type of inhabitants varied according to different times of the day and days of the week. This highlights the importance of understanding the temporal nature of the area and the types of activities that occur during specific times, to better plan and design for the community. The study also identified some existing setups of the commercial streets in Nugegoda, which has encouraged people to gather in specific spots due to the availability of certain features in the built environment. Inhabitants were attracted by specific built environments within an area regardless of their type. (Nugegoda Flyover Junction – Under the Bo tree and in front of Nolimit, Super Market Junction – In front of the snack bar, Stanely Thilakaratne Mawatha – Under the shade of trees row). This created a shared behavior pattern among all inhabitants and enhanced their interaction. Overall, the findings suggest there is a higher potential to enhance the sense of community in Nugegoda town by creating a well-built community center for the transitory population.

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UTILIZING MODULARIZATION TO ACHIEVE SUSTAINABLE CONSTRUCTION

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Abstract: In today's world, there is a growing recognition of the importance of environmental concerns and the need for more effective and eco-friendly building practices. As a result, sustainability has become a crucial factor in the construction industry. This article explores the use of modularization as a sustainable approach in construction projects and presents a case study as an example. From the outset, our team intended to integrate Prefabricated Prefinished Volumetric Construction PPVC) modules into the design of the villa. We meticulously examined each detail of the architectural, structural, and MEP aspects to ensure that efficiency was maximized while time, labor, and cost were minimized. The incorporation of modular technology has provided us with ample advantages, and we have seamlessly integrated these into our pioneering approach. Using PPVC drastically reduced the construction time since the modules were fabricated off-site. The module fabrication process was done simultaneously with the site preparation/foundation process so that the continuous supply of modules was possible during the on-site construction. We reduced the manpower requirement and involvement of sub-contractors. PPVC can improve productivity by up to 40% in terms of manpower and time savings, depending on the complexity of the projects. According to this study, the project has achieved significant success in reducing construction waste at all stages and has enhanced the overall efficiency of the building process. The project has effectively decreased its carbon footprint by utilizing modularization in various technical aspects. The case study demonstrates how modularization can be a practical and effective solution for addressing sustainability issues in the construction industry.

Keywords: Modular; PPVC; Sustainable; Efficient; BIM

1. Introduction

The Modular Construction used and studied in detail in this paper is widely known as the PPVC method in many countries, or as MIC (Modular Integrated Construction) and DFMA (Design for Manufacture and assembly) in some countries. Prefabricated Prefinished Volumetric Construction (PPVC) is a construction method used all over the world where three-dimensional modules are molded with internal finishing and fittings in an off-site production plant before being moved to the construction site and installed.

Benefits of Prefabricated Prefinished Volumetric Construction from a sustainable point of view (Building and Construction Authority),

- **Productivity**

Using PPVC will drastically reduce the construction time since the modules are fabricated off-site. The fabrication process can be done simultaneously with the site preparation/foundation process so that the continuous supply of modules can be done during the on-site construction. The off-site fabrication and the relatively easy assembly of modules allow the contractors to use less manpower including a reduced number of sub-contractors. The decreased on-site involvement will further save time since setbacks such as unfavorable weather conditions will not have a big effect on the project timeline. PPVC can improve productivity by up to 40% in terms of manpower and time savings, depending on the complexity of the projects (ARCADIS SINGAPORE PTE LTD, 2017).

From a sustainable point of view, the reduced construction timeline and the reduced amount of labor directly reduce the construction waste produced by the laborers at the factory during their respective tasks, and, the number of resources that will be required to maintain the facilities during that time will be less.

- **Quality**

Off-site fabrication of the modules further increased the quality of the construction since the controlled environment in the facility with thorough supervision ensured the end product would have the desired mechanical properties with perfect consistency and higher quality (Chain, 2018).

The higher quality will result in fewer rectifications hence, this is directly related to increasing the sustainability of this construction method.

- **Safety**

The decreased amount of on-site activity and the reduced involvement of manpower will increase construction safety. Especially, the high involvement of technology and machinery will also increase site safety as the corresponding site accidents will be reduced.

- **Environmental Impact**

The prefabrication of the modules will result in a significant reduction in on-site construction waste. Furthermore, dust and noise pollution will be minimal, resulting in less environmental pollution. Since this is a factory product, it reduces the net carbon footprint when compared to conventional construction methods. Modular construction has a significantly lower carbon footprint when compared to projects with conventional construction methods.

This method was introduced to Sri Lanka by the International Construction Consortium (Pvt) Ltd in 2021. Since then, the PPVC technology has been utilized and improved vastly in a way that is suitable for this region of the world, and during this journey, multiple ways and means to achieve sustainability using this construction method were experimented with and utilized. The following case study, which is a luxury villa project completed in Akuregoda, Sri Lanka, is used in this context to discuss it further.

2. Case Description

The client brief required 14 houses to be accommodated within a 0.3716 Hectare land. Apart from the tight site restrictions, the site required.

- Location – Akuregoda, Sri Lanka
- Area of a Villa – 2200 ft^2 (excluding roof terrace)
- Specifications,
  a. Living and Dining Area
  b. 4 Bedrooms
  c. 3 Bathrooms
  d. Maid's bathroom and bedroom
  e. Pantry
  f. Large rooftop terrace and balconies
  g. Car park

This project was a complete project by the International Construction Consortium (Pvt) Ltd which was their first Commercial Modular Project. Each villa was a combination of 11 different PPVC modules.

3. Architectural Concept

The design intention of the house was to create a compact, simple, functional, and aesthetically pleasing space using Modules. This could accommodate larger families, who may not be able to live in an apartment.
The modules were arranged to bring out a modern façade suitable for an urban context.

- **Sustainable practices**

Minimum damage to existing trees. Due to the large number of trees along the external road around the site, it was decided to have the entrance to the individual land plots from an internal road.

The site was sloppy with a height difference of around 3m. The road level of the house entry level was decided to match the cut and fill soil volume. Retaining walls were used only where it was essential.

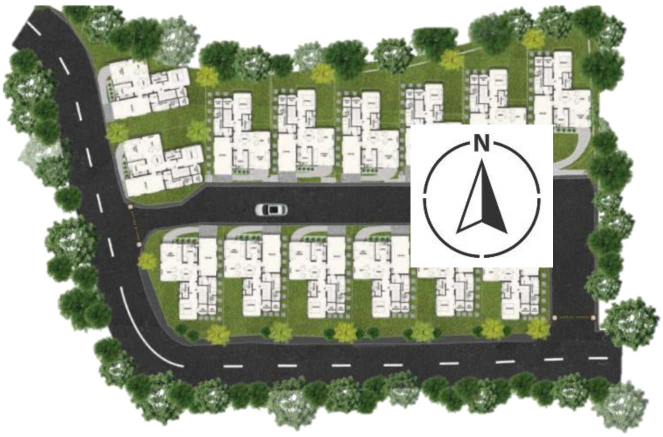

Figure 1: Land Layout.

Considering the sun's path, windows have been placed on the North and South facades of the houses. This will considerably reduce heat gain and reduce the need to operate air conditioning.

Figure 2: Architectural Layout.

The type of door and window openings have been kept to a minimum which has resulted in more standardisation, promoting sustainability.

- **Innovative techniques used such as the staircase module, car park module, etc.**

The architectural concept was to maximize the space within the house. For this, special-purpose modules were designed as a staircase and a car park.

a) Staircase Module

The Staircase Module was initially designed for the Housing Project in Akuregoda, which turned out to be successful. The Dimensions of the Module were utilized perfectly to accommodate a wide steel staircase connected to the slab of the top module while another smaller staircase connected the lobby and the terrace level. This became the main feature of the house. The top-hung windows on the upper stair landing and rooftop level allow hot air generated on the ground floor to escape and it enhances the internal thermal comfort. The precise planning allowed the space under the staircase to be utilized as a storage area accessed from the bedroom, while the other part was used as part of the maid’s toilet and maid’s room.

Figure 3: Staircase Module.

b) Car Park Module

The Car Park was designed to utilize the maximum space available within a module.

Figure 4: Car Park Module.

- **Specifications and materialistic approach**

Material available in the local market was proposed to reduce the imports. All design details were done considering modular construction. The color scheme was designed to complement the surrounding green landscape and the Defence Ministry building close.

- **Architect imagination and photographic evidence of the inside layout.**

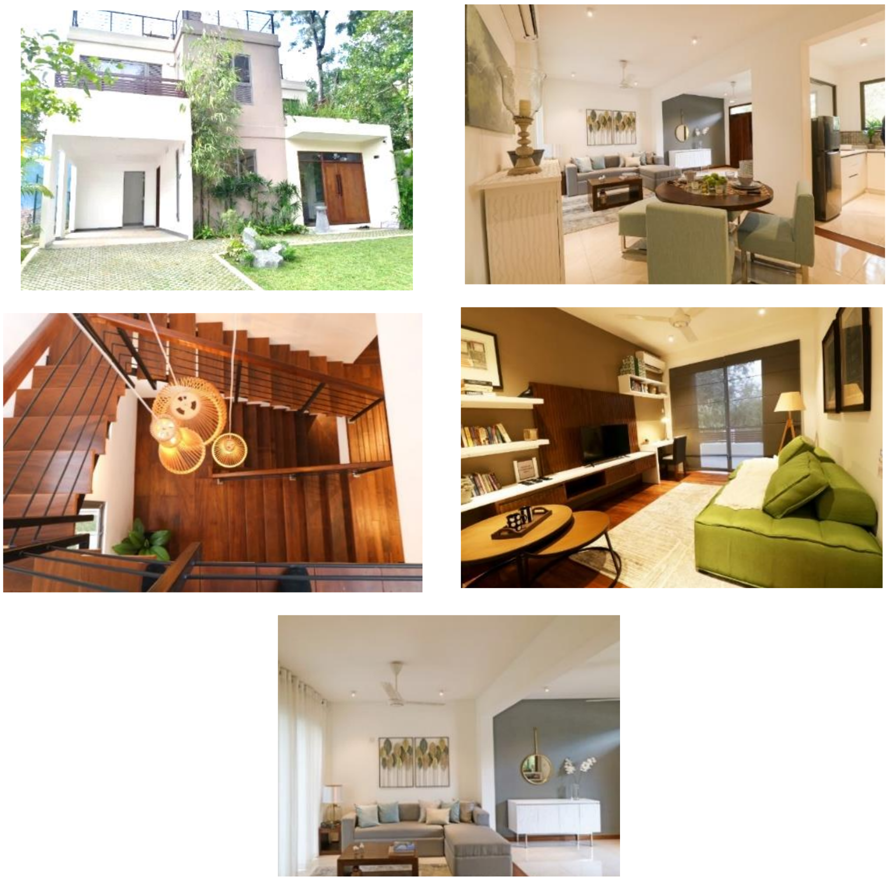

Figure 5 : Architectural Aspect.

4. Structural Concept

The structure of the house was specifically designed utilizing the maximum potential of the PPVC technology. The design was done in a way that can accommodate all the recesses and MEP provisions without compromising the structural stability while optimizing the material usage. During the structural design, all the anticipated loading combinations were assumed considering the stresses generated during casting, lifting, and erecting. Also, the reinforcement layout was designed to absorb the vibrations as much as possible without transferring them to the internal finishes and fixtures since the module must be transported more than 20 km away from the fabrication yard.

The vertical and horizontal connections between the modules were critical since the stability of the entire structure depends on the strength of those connections.

The structure was designed to minimize the in-situ construction and to maximize the percentage of construction done at the factory. The distribution of on-site and off-site concrete usage is compared in the following table.

Table 1: Percentage of Concrete Usage

	Off-Site (at the factory)	**On-Site**
% of Concrete Usage	81%	19%

There was no falsework and formwork used for concreting work as all ancillary structural elements such as balconies, large flower troughs, and canopies. These structures were designed as precast products and linked to the PPVC module.

Figure 6: Large flower trough and canopy.

5. MEP Concept

The following services were carried out under MEP according to the client's requirements:

1. Water supply, drainage, and stormwater drainage
2. Mechanical ventilation and air conditioning
3. Electrical/ ELV

In modular construction, it is a must to maintain accuracy and minimize the number of revisions when designing the MEP provisions. It was important to identify the critical reinforcement locations so that the MEP fixtures and services could be designed in a way that would not affect the positioning of those reinforcement bars. All the necessary openings, concealed component recesses, etc. were included in a way that will not affect the structural performance of the module.

The BIM (Building Integration Modelling) Model was initially developed with high precision for architectural, structural, and MEP with exact coordination drawings developed with services, and those were checked multiple times before finalizing. The 3D model of the modular house was printed to get a proper idea of the house and the positioning of the modules.

Since all walls and floors are concrete, it was difficult to lay plumbing lines along walls, especially drainage pipes. Therefore, a lightweight dummy wall was designed for laying the plumbing lines in each bathroom.

It is essential to maintain the connection and continuity of the components, including wiring, conduits, cable trunkings, and cable trays between modules. LV circuits were designed module-wise. Concealed and surface conduits can be applied in the PPVC modular system.

The electrical and ELV systems were optimized to use the minimum length of conduits. Pre-cutting and pre-fixing conduits, pipes, and other MEP accessories led to save immense amount of labor and time. This enhanced productivity by avoiding delays. Also, it decreased the percentage of MEP waste and increased the possibility to pre-plan the use of off-cuts further.

6. Timeline

The entire project was completed within 12 months.

Table 2: Project Timeline

Item	Month											
	1	2	3	4	5	6	7	8	9	10	11	12
Fabrication	■	■	■	■	■	■	■	■	■	■		
Fit-out work	■	■	■	■	■	■	■	■	■	■	■	
Foundation		■	■	■	■	■	■	■	■	■		
Transportation and Erection				■	■	■	■	■	■	■		
In-Situ Work				■	■	■	■	■	■	■	■	■

Using Conventional Construction would take an estimated 2 years and hence, we were able to **save 50%** of the construction time.

7. 3D Printing

3D printing technology was used to enhance the capability of illustrating and demonstrating the concept to all the levels of construction team. This reduced the considerable time for introducing this innovative concept.

Figure 7: 3D Printed Modules.

8. BIM

All design aspects were developed using the latest BIM (Building Integration Modelling) techniques. Unlike the conventional design approach, all the clashes were pre-identified and solved during the design stage here. Commercially available software was used for this.

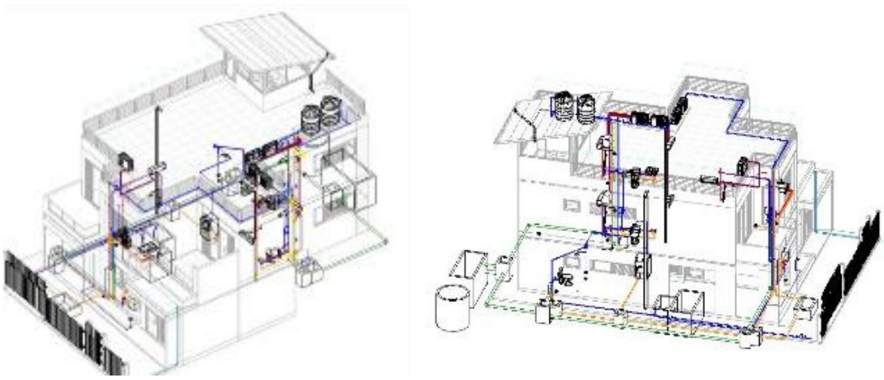

Figure 8 : BIM models of the house.

9. Conclusion

This project was a huge learning curve for everyone who was involved and the sustainable outcome it had was immense. The material wastage from the entire project was almost negligible because of the pre-planning done using BIM technology. The total labor savings in this project was almost 50% and the time saving was almost 40% when compared to if this project was done in situ. The project was completed within the scheduled timeline since most of the construction was done at the factory without any interference from external factors such as extreme weather conditions. The methods used had a good sustainable impact in terms of material saving, reduced wastage, and most importantly, a reduced carbon footprint from the entire project.

Acknowledgments

We would like to thank the International Construction Consortium (Pvt) Ltd for allowing us to be a part of this amazing project and the learning curve.

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ANALYSING THE DAYLIGHT DISSEMINATION IN HIGH-RISE INTERIORS: A ZONE-SPECIFIC CASE STUDY AT SAINTGITS

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Abstract: Rapid urbanization has systematically lured the inhabitants to expend more on plentiful means to maintain decent levels of indoor occupant comfort. Greater levels of space constrain in built environments demand higher physical proximity among their built structures. Since the inflow of natural lighting is extremely dependent on the availability of hindrance-free regions at any geographical locale, it is appreciable to simulate, visualize, and quantify the amount of achievable indoor daylight. This piece of work involves zone-specific analysis that encompasses both experimental and architectural modeling to learn the dissemination of natural lighting at the sixth level of a nine-storied built structure at SAINTGITS, a prominent technological institution down south of the Indian subcontinent (9.5100°N, 76.5514°E). The analysis explores a set of design modifications, including fabric openings, internal partitions, and site orientations that can effortlessly ascertain the lowest levels of artificial lighting loads during the daytime. Furthermore, this work quantifies the illuminance level in terms of the attainable daylight factor (DF) in indoor regions: regions with DF > 2 are deemed adequately lit throughout the active hours of any normal day. This work provides a direct indicator to envisage and accomplish one of the seventeen Sustainable Development Goals (17 SDGs) of the United Nations: Sustainable Cities and Communities (SDG11).

Keywords: SAINTGITS; Daylight factor; High-rise structures; Sustainability; 17 SDGs; SDG11

1. Introduction

Built environments consume the largest slice of energy and it has grown significantly over half a decade, since 2017 (Huo, 2017; Jrew, 2019). Subsequently, most of the semi-rural regions are getting transformed at faster rates, and the energy demand is intense (Kosorić, 2021; Kubba, 2012). Numerous initiatives are in place to inculcate and implement sustainable transformation in habitats (Varghese, 2020). Since built structures are an inevitable part of any built environment, their outer envelope needs to be well-designed to facilitate liveable indoor regions (Ascione, 2019; Shan, 2014). Hence, the design aspects of the outer façade of any built structure stand vital: it determines the quantum of energy expended (Huo, 2017; He, 2022). Greater voicing to practice sustainability is a worldwide need, especially to mitigate the adverse effects of atmospheric pollution and climate change (Balendra, 2024; Thottathil, 2011).

Among the plentiful design aspects, the site orientation and the window wall ratio (WWR) explicitly influence the indoor comfort conditions (Hinrichs, 2017; Ji, 2023; Li, 2021). Lighting design is one of the contributors that can improve indoor liveability (Carmody, 2004; Zelenay, 2011). Ironically, in certain rural locales in tropical climes, the lighting design domain remains less investigated (Kosorić, 2021; Wei, 2022). Since the cooling load stands first and explicitly drains the corpus fund, the lighting load expenses remain unnoticed (Mastellone, 2022; Wu, 2017). To remain specific, light pollution is one of the emerging environmental concerns in the Indian sub-continent (Koushik, 2022).

As an indigenous initiative at the SAINTGITS campus, most of the Sustainable Development Goals (SDGs) are continually explored and analyzed (Varghese, 2022; Thomas, 2018). Most of the in-campus research works are oriented to address the eleventh SDG of the United Nations (SDG11): Sustainable Cities and Communities (Thomas, 2020; Varghese; 2017; Varghese, 2015). This piece of research intends to help by reiterating the relevance of windows, their influence on the effective dissemination of natural light to the whole of the indoor regions, and the various design enhancements in any built structures in tropical climes.

2. Methodology

The work comprises of two main stages - architectural modeling and experimental analyses to determine the extent of daylight dissemination in the indoor regions of a high-rise-built structure at SAINTGITS, a renowned autonomous institution in South India (figure 1).

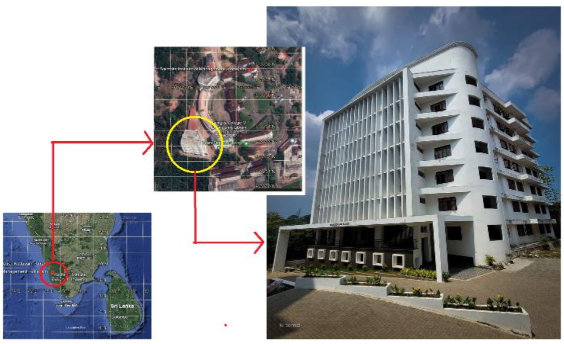

Figure 1: High-rise structure at SAINTGITS Campus: the Abdul Kalam Block (AK Block).

The architecture model that structurally emulates the entire sixth level of the Abdul Kalam block (AK block) is modeled in Design Builder, a versatile modeling and simulation software, and widely used by building energy specialists and architects. The inbuilt Energy Plus module (an open-source freeware) performs all the background analyses related to multiple domains of energy that are being expended in any built environment. The experimental investigations at the secondary stage have helped to quantify the indoor illuminance level to stay following the daylight factor (figure 2).

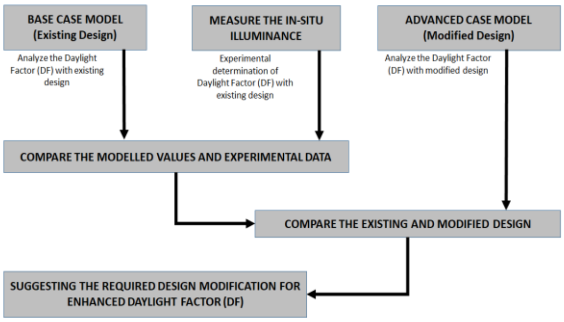

Figure 2: Detailed block diagram to represent the workflow and methodology adopted.

This piece of work better fits as a pre-constructional analysis to ascertain the proper availability of daylight in the indoor regions of the AK block, throughout the active hours of any regular day.

3. Results and Discussions

The results are systematically arranged under three broad sections categorized as (i) Base case model: Existing design, (ii) Advanced case model: Modified design, and (iii) In-situ indoor – outdoor illuminance level cum daylight factor (DF).

3.1 Existing Design as Base Case Model

The openings on the outer fabric at the sixth level of the AK block were analyzed with three different sub-cases to showcase the stark difference related to the disseminated illuminance in the indoor space. Since the whole floor space accommodates conventional classrooms, faculty cabins, general amenities, central corridors, and other common regions, this analysis provides vital information on the zone-wise daylight infiltration at all of these regions. The wire-frame model for the complete outer fabric with existing window openings and interior partitions was considered as the base case scenario to vie with the real-time indoor illumination levels (figure 3).

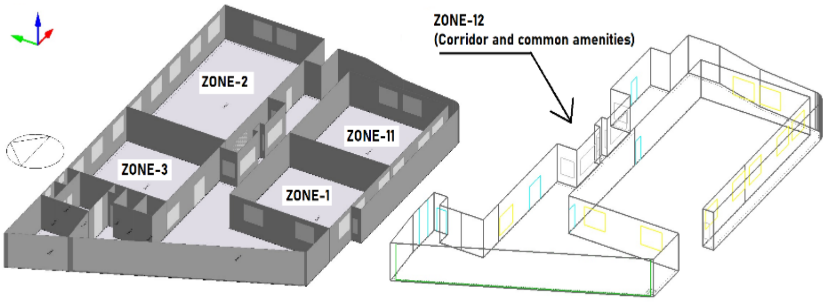

Figure 3: Three-dimensional wireframe and rendered view with interior partitions and fabric openings created in Design Builder.

Though the common amenities and corridors are an integral part of the existing floor plan, for better illustration and discussion, the analysis was performed zone-centric, rather than floor-centric (figure 3). Moreover, since the indoor thermal aspects are out of the scope of this piece of work, the zone-centric approach holds validity in all aspects. Therefore, each of the four prominent zones (Zones-1,2,3 & 11) was separately studied to compare, both position-related and zone-wise infiltration and thereafter, the dissemination of natural light into the indoor regions (figure 4).

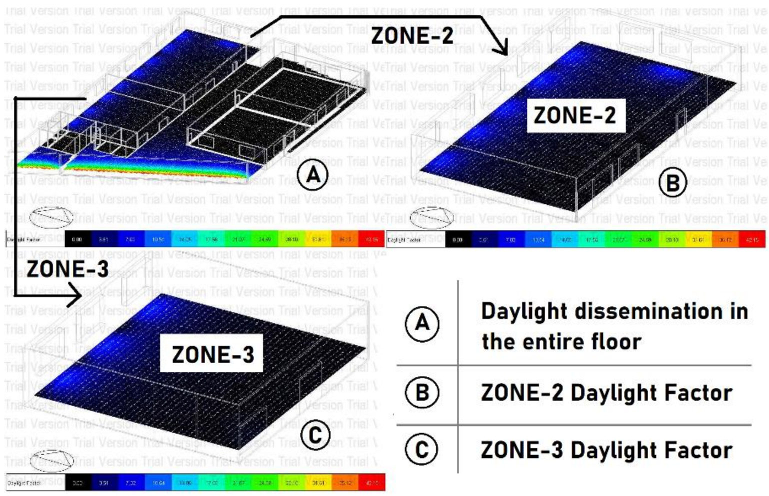

Figure 4: Base case model: Floor-specific dissemination of daylight factor (DF) into the indoor regions of Zone-2 and Zone-3.

In Zone-3, a total of 1558 nodes were analyzed over an area of 425.8m^2 to quantify the extent of daylight penetration through the outer façade into the indoor regions. On the horizontal plane of analyses (assumed at 0.75m from the respective floor level), 75% of the floor space was found to be poorly lit (DF < 2%). Similar was the case with Zone-2 too, except for window openings on two adjacent walls. Out of the 2584 nodes, 1747 nodes (68%) came under the poorly lit category. Hence, the interiors of both zones (Zones 2&3) were deprived of adequate illuminance to provide essential visual comfort to their occupants.

At certain unique site locations, the floor plan orientation contributed significantly vis-à-vis the dissemination of indoor illuminance. However, the site under our present study has negligible contribution towards orientation-dependent DF in the indoor spaces. Therefore, the succeeding section (section 3.2) right away analyses the DF dissemination for an improvised design.

3.2 Advanced Case Model

Improvisations were done on the outer fabric such that, the enlarged openings facilitated enhanced illuminance in the indoor regions. Since the Window-Wall-Ratio (WWR) is directly dependent on the area of the outer fabric opening, the advanced design has ensured the values of WWR stay within the permissible levels as mandated by the standards of ASHRAE. A stark side-by-side comparison of the existing and advanced design for Zone-2 is in Figure 5.

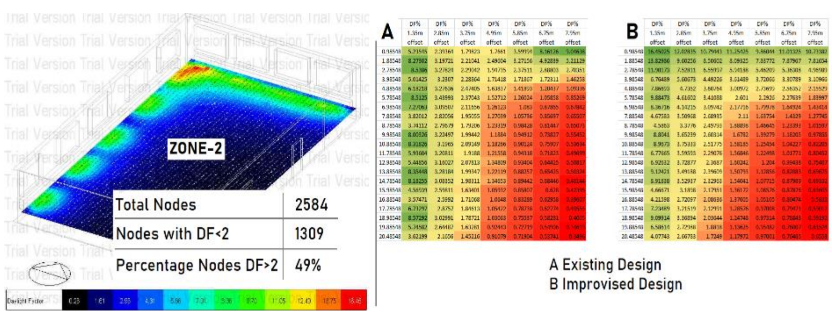

Figure 5: Advanced case model to compare the difference in the dissemination of Daylight factor (DF) in existing and modified design.

In Zone-2, while the other conditions remained unaltered, the daylight infiltrated to gain 17% more floor area under adequate or strongly lit than the base case model. The DF values at a few sets of linearly arranged points, parallel to the larger wall were considered to learn the penetration and dissemination enhancement gained by the advanced case design (figure 6).

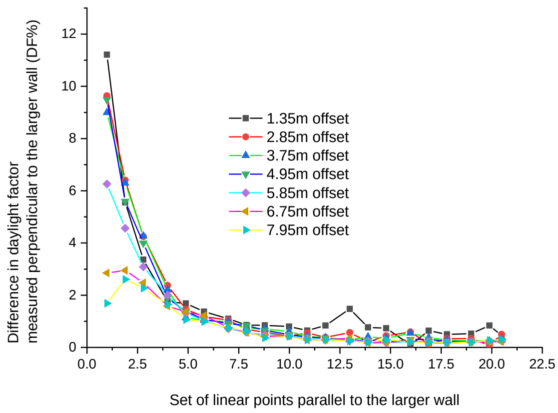

Figure 6: Explicitly evident improvisation in daylight factor (DF) achieved at the indoor regions of Zone-2: An analysis at different offset distances from the larger wall.

While completing the analysis of the improvised design, the maximum and average values of the additionally achieved daylight factors were 11.21% and 1.25% respectively (figure 6).

3.3 In-situ Measurement of Illuminance and Daylight Factor (DF)

The values of average illuminance, both indoor and outdoor, were recorded on multiple occasions. In one instance, during the afternoon hours of a normal working day, the same was measured with a handheld mobile application installed on an Android instrument (Octa-core Max 2.0GHz).

The data pertained to a few pre-determined positions in Zone 2 and was measured perpendicularly from the larger wall at cumulative offsets 1.35, 2.85, and 4.95 meters. Further, the daylight factor (DF) was calculated by keeping Eq. (1) as the reference.

$$\text{Daylightactor} = \frac{\text{Indoor illuminance}}{\text{Outdoor illuminance}} \text{ x } 100\% \tag{1}$$

All the DF values related to Zone-2 are tabulated in Table 1 to serve as one of the comprehensive in-situ data sets that facilitates further analyses.

Table 1: Indoor - Outdoor illuminance and DF at Zone-2

Record points	**Illuminance (Lux)**				**Daylight Factor (%)**		
	Outdoor 2.5m	***Indoor 1.35m***	***Indoor 2.85m***	***Indoor 4.95m***	***Indoor 1.35m***	***Indoor 2.85m***	***Indoor 4.95m***
Z2-1	5808	568	345	205	9.78	5.94	3.53
Z2-2	5808	488	286	191	8.40	4.92	3.29
Z2-3	5808	469	254	186	8.08	4.37	3.20

Z2-4	5808	488	277	177	8.40	4.77	3.05
Z2-5	5808	411	219	158	7.08	3.77	2.72
Z2-6	5808	621	201	143	10.69	3.46	2.46
Z2-7	5808	652	190	108	11.23	3.27	1.86

In the last phase, the modeled and calculated values of DF were compared to analyze the percentage deviation (figure 7). Zone-2 being the largest, was studied to the fullest. At all times, the values of the daylight factor calculated from real-time illuminance data stayed at higher levels than the modeled output. One of the major reasons was the adopted weather file. The unavailability of standard weather data for the exact locale (9.5100°N, 76.5514°E) prompted the induction of a reasonable proxy.

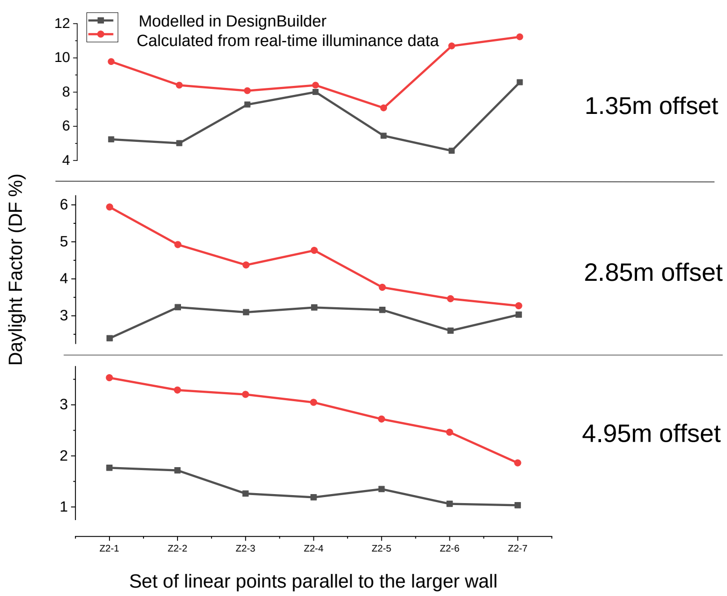

Figure 7: A stark comparison of in-situ results and modeled values at three offset distances from the larger outer façade.

The trend was almost similar and realistic at all nodes. More experimental iterations (instances) were conducted during different days and hours to learn and reaffirm the trend. For the same zone (Zone-2), a few more sets of in-situ data (about indoor illuminance) were recorded on multiple days over four instances using another hand-held device. In each instance, the data were taken from 39 pre-determined record points as per the floor plan exhibit (figure 8).

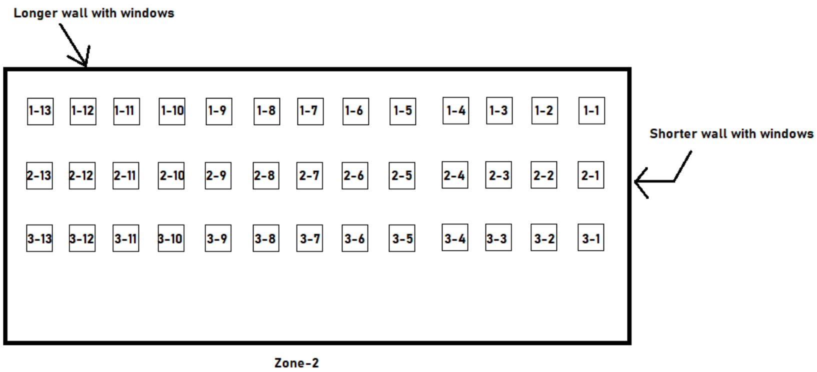

Figure 8: Floor plan at Zone-2 for data collection from 39 record points during a single instance.

Thirteen record points were earmarked at each row and these were aligned parallel to the longer wall with windows. The 3 rows were separated at 1m distance from the adjacent. It helped to learn both the device-dependent and instance-dependent variation of illuminance level at the indoor regions of Zone-2 (figure 9).

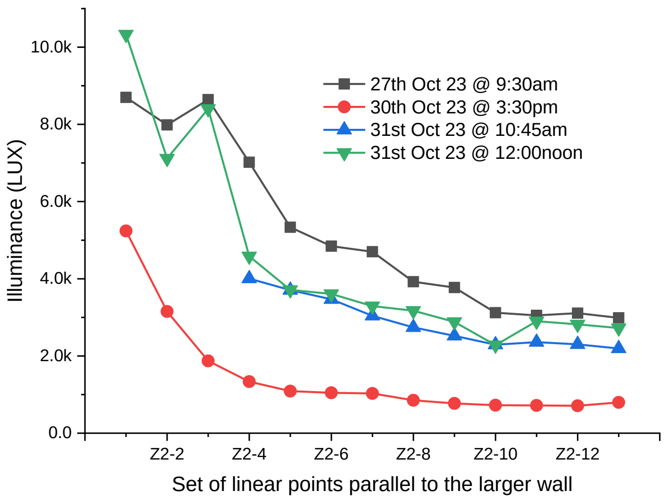

Figure 9: Indoor illuminance at Zone-2 over 13 farthest record points for multiple instances.

The illuminance values explicitly reflected the device dependency, and the trend was as expected. In all four instances, the maximum illuminance values were at the record points, located nearer to the window opening on adjacent walls. Therefore, in a nutshell, the illuminance values from both the architectural model and in-situ measurements shared a common trend and the trend was predictable.

4. Conclusion

This work proposes a modified design to enhance the dissemination of daylight into the interior regions of a conventional lecture room, house at the 6^{th} level of a multi-storied built structure at the SAINTGITS campus. As the existing openings on the outer wall fabric could provide adequate natural lighting at only 32% of floor space (in Zone-2), an improvisation proposal was inevitable. The proposed fabric openings on outer walls enhanced the natural daylight infiltration by 17% than the existing. Moreover, the proposed design ensured the WWR to stay within the permissible levels as mandated by the standards of ASHRAE. Similar modest initiatives that could curtail the energy expended in built structures will certainly contribute towards the transition to accomplish one of the seventeen Sustainable Development Goals (17 SDGs) of the United Nations: Sustainable Cities and Communities (SDG11).

Acknowledgments

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THE CURRENT GROWTH OF GREEN ENERGY AND ITS DEVELOPMENT IN INDIA

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Abstract: Green Energy has become the norm of development in the world, with the increased environmental degradation and global warming problems over the past decades. At present, all developed, developing and underdeveloped countries are progressing towards the development of the green energy as much as possible. This paper particularly takes the case of India and highlights the current stand and policies of the government in regard to the Green Energy. The paper also covers the development of Green Energy so far in the country India and includes major projects in the country which are assisting its growth. Some research gaps were found after considering numerous scientific and research papers published over the years. Some graphical analysis will be performed from different sources in order to understand the trend and possible future growth of Green Energy in the country, to support the study.

Keywords: Green Energy; Sustainable Projects; India; Development; Solar Power

1. Introduction

The renewable energy sources that arrive in the power grid which support the charging of the smartphone or lights in the room, cannot be distinguished from traditional energy sources, but the difference in their impact on the environment is big. With the increase in the awareness of humans, they are realizing the negative impact of the ongoing development with the help of traditional energy resources and the significance of transitioning to renewable resources, which even consumers are also realizing. For the major sustainability in the power grid, Green Energy is a good solution, nevertheless, people often misunderstand the term and interchangeably use it with renewables. For example, the United States energy market provides a variety of not only products but also services with green energy, which is also known as green power which is a small group within the mentioned choices. Many people think it is renewable energy, nonetheless, there is a strong difference between them. In this case, the EPA which is called as Environmental Protection Agency says that green energy gives the maximum benefit to the environs as well as comprises power generated by geothermal, solar, low-impact hydroelectric, wind, biogas, as well as some suitable biomass sources. Though renewable energy includes the same sources as green energy, their respective impact on the local as well as global environs, creates a major difference between them. However, by buying green power, people can aid in a number of renewable energy projects as well as technological investments, which further aid in their growth. In simple words, most sources of green energy are also considered renewable but not all sources of renewable energy can be completely green. For example, emission of some carbon is linked with the processes utilized to produce energy which can be for buildings, etc. then that source of renewable energy would not be regarded as green, as it is harming the environment considerably less in comparison to the conventional energy sources.

1.1 Some Major Types

In this subsection, some major types of green energy will be discussed in brief:

- Hydropower
- Biofuels
- Solar Power
- Geothermal Energy
- Wind Power
- Biomass

Hydropower: It is also known as hydroelectric power, which is a major type of green energythat utilizes water's flow in the dams, streams, rivers, etc. to generate electricity. In the case of India, is ranked fifth in the world for the highest hydroelectric power capacity.

Biofuels: Instead of burning biomass, which is an organic material, it could be changed to fuels like biodiesel as well as ethanol, which are having great demand in the long run. In recent years, India has been working on increasing their usage in the future.

Solar Power: this type of green energy is mostly generated by the assistance of photovoltaiccells which can internment the coming sunlight as well as change into electricity. In India, they could be even found in small villages on a small scale, in big universities, or ona large scale in the form of Solar Farms.

Geothermal Energy: It is a type of green energy that utilizes thermal energy which has been stored under the crust layer of the planet. However, the drilling procedures must be carefully checked to make it completely green. In India, it is found in the union territory of Ladakh and states like Uttarakhand, Himachal Pradesh, Maharashtra, and Chhattisgarh.

Wind Power: This type of green energy utilizes the power of the air's flow around its surroundings to push the turbines to produce electricity. India has made many Wind Farms to use this type of green energy, which can be found in Indian states like Gujrat, Tamil Nadu, Rajasthan, Karnataka, Andhra Pradesh, and so on.

Biomass: It is necessary to prudently manage this renewable resource to make it a green energy source in the true sense. Sawdust, wood waste as well as combustible organic agro waste, are used in Biomass Power Plants to generate energy. In India, most of its states are using biomass energy and more such projects are expected to come up in the future.

1.2 What is The Need for Green Energy?

In the current times, it is essential to decrease the emission of carbon, as well as inhibit any more harm to the environment, which could be achieved through the use of Green Energy instead of traditional reliance on non-renewable sources of energy. Then, Green Energy projects are also creating more job opportunities, especially for the locals in that place, and investment in Green Energy is expected to bring long-lasting sustainable returns. Hence, the Indian Government in the recent decade increased its focus on developing Green Energy and planned to replace non-renewable energy slowly and steadily in the future. Green Energy has the potential to completely replace fossil fuels, but it is important to use a variety of Green Energy sources based on the suitability of the location of a place. However, these things could be achieved in India, but more investment along with technological development is necessary to support it throughout the country. Also, in the future, the cost of non-renewable sources of energy will increase significantly with the decline of these resources. This will automatically make the Green Energy as an economical option to replace non-renewable sources of energy.

1.3 Objectives

There are several objectives of this study which are as follows:

- To understand the concept of Green Energy and the difference between Green Energyand Renewable Energy.
- To understand the need and types of Green Energy.
- To understand the gaps in the current research and the Green Energy projects in India.
- To understand the market and future of Green Energy.

2 Motivation

India is a major developing country that is progressing in the path of development at a fast rate, but it is also important that the development should be sustainable in the long run. Currently,the Indian Government has been focusing on green energy as well as on renewable sources. Due to this, the author felt that it is important to understand the development and current progressof his home country in the area of Green Energy. Further, it was required to understand how much favor the current policies are regarding Green Energy and their potential in the future.

3 Literature Review

Dar et al. (2022) studied green energy projects and they worked not only on penalizing measures but also on the current optimization, which was intended for their studied area. They also tried to gain an understanding of the effect of the emission of carbon dioxide on the circular economy, in their paper. Wang and Xu (2023) studied renewable energy projects and they worked on their development as well as on green investments. They further examined the potential of the fifteen Regional Comprehensive Economic Partnership member countries, which are progressing in the direction of green investments, from the beginning of the 21st century till the year 2021, through their study. Daoudi et al. (2022) studied the installation ofthe 1st onshore wind farm, and analyzed it, which is near the green energy export project of Morocco – UK, through their study. Sunio et al. (2021) studied the logistics of sustainable financing, and they worked on finding out how the greening of banks affects it, through their study. They considered the case of the country Philippines, particularly where renewable energy projects in which the bank was lending to the merchant, to accomplish their given study. Brauner et al. (2023) worked in the direction of green hydrogen, and they compared the visions of Africa as well as Germany, in addition to the anticipations in the case of the H2Atlas – Africa project, to obtain the desired study outcomes. Taghizadeh-Hesary et al. (2022) studied hydrogen projects and they worked not only on their economic feasibility but also on green finance. Dimou and Vakalis (2022) studied the transitions of green energy in the case of isolated grids, and they worked on analyzing them on the techno-economic aspects. To accomplish their study, they considered Ai Stratis-Green Island as their study case. Liu et al. (2021) studied green energy PPP projects and they worked on an evolutionary game method that was intended for the behavioral strategies of the private sector in such projects in China. Chen et al. (2021) studied green energy infrastructure and they worked on how it affects the productivity of the firms, where they supported their study by considering the case of the Three Gorges Project, which is present in China. Shrimali and Jindal (2023) studied green energy technologies and they worked on the design of the policies to make the country India a self–reliant one in this direction. Nikhil etal. (2023) studied not only the need for green hydrogen, and the release of CO_2, but also hydrogen's geo–storage potential; and they worked on analyzing them to decarbonize the operations of industries, especially in the case of India's southeastern coastal region, to obtain the desired results. Sareen et al. (2023) studied the production of green hydrogen, and they worked on estimating it using the Deep Learning method in Indian conditions. Harichandan et al. (2023) studied the green hydrogen economy, and they performed a serious as well as methodical review of past studies by considering the case of the country India. Ingle et al. (2022) studied marine energy projects and they worked on incorporating the method of multi-trophic aquaculture, to restore as well as manage India's coastal ecosystems, through their study. Gupta et al. (2023) studied green hydrogen and they worked on prioritizing its feasibility as well as prospects as a renewable source in India. Singh et al. (2023) worked on renewable energy policies in addition to research in India to gradually reduce the use of coal, where they considered the Paris Agreement as well as the later success, along with the post-Glasgow Climate Pact's potential, through their study. Khare et al. (2023) studied the multi networks of green energy systems which are considered sustainable ones, and they worked not only on their operational management but also on their design in the Indian conditions. Abhyankar et al. (2023) studied economic energy independence in India's case, and they worked on harnessing it by considering the progress of the country in this area till the year 2047 in the future, to understand its road in the direction of a clean future as well as energy independence, to obtain the desired study outcomes. Khare et al. (2023) studied hydro energy and they worked on evaluating its perspective with the assistance of data analysis by using Indian rainfall data sets to accomplish their study. Pandit et al. (2023) studied hydropower and they worked on understanding the pros as well as cons of this energy option in the Indian scenario, by reviewing the past studies in addition to discussing many anxieties associated with the hydropower sector of the country. They further inspected scientific proofs, considered geopolitical aspects, and analyzed the need for energy policies, in addition to highlighting the path of future studies on the policy of hydropower in the country to the current climate change.

4 Research Gaps

After going through several published scientific and research papers, only the recent ones were selected. It was found that in recent years, research has been going on green energy and projects, but more focus was especially given to hydropower energy. To reach the target of Net Zero Energy, green energy will play a major role and to develop it further, it is required for researchers to focus equally on other sources of energy as well.

5 Main Focus of the Paper Along with Issues and Problems

This paper focused on explaining green energy and its necessity in the current times, particularly in India. Then, some major projects and policies in India in its support were covered in this study. However, there are problems and issues also in implementing green energy projects andtheir usage, which shouldn't be neglected. A lot of documents are required to start a green energy project, which are important but at the same time, many contractors would prefer not to go for such projects to avoid the difficulty of starting such projects. Then, many contractors, people, and companies still don't understand the importance of green energy projects as they think that at present things are already fine for them with conventional non-renewable projects. Lack of awareness is still there, along with people who are inflexible and do not consider future problems, which are causing hindrances in the development of green energy projects. Also, green projects are not producing the anticipated amount of employment in reality and inconsistent amount of employment, which are also major hurdles to overcome.

6 Major Projects

In this section, some major Green Energy Projects are discussed which are:

- Green Energy Corridor
- Amazon's Wind and Solar Projects
- Puga Geothermal Energy Project
- Bhadla Solar Park
- Rewa Solar Project
- Jaisalmer Wind Park
- Muppandal Wind Farm

Green Energy Corridor

The Indian Government launched the project named Green Energy Corridor in the financial year 2015-16 to synchronize the generation of overall electricity from renewable sources including tidal, solar, hydro as well as wind, with the assistance of the traditional national grid in the country. This project is an intrastate or interstate power transmission system that has been going on in 8 states of the country namely Himachal Pradesh, Tamil Nadu, Maharashtra, Gujrat, Rajasthan, Madhya Pradesh, Andhra Pradesh, as well as Karnataka. There are two phases in this project, which are Phase 1 and Phase 2, where the latter phase of the project is still in progress.

Amazon's Wind and Solar Projects

The Wind and Solar Projects of Amazon are expected to increase jobs as well as economic investment in India. A novel 198 MW wind farm was declared by Amazon in the state of Maharashtra in the place named Osmanabad, which makes the company's fifty solar as well as wind projects across the country in addition to exceeding the capacity of 1.1 GW of renewable energy. The Osmanabad Wind Farm Project is the 7th utility-scale renewable energy project andin the past, the company also announced 43 rooftop solar projects, which is expected to help the country to replace non-renewable energy with green energy up to a certain extent. These projects assisted more than twenty thousand six hundred full-time equivalent jobs in the surrounding areas in the year 2022. Further, USD 349 Million investment was brought from the year 2014 to the year 2022, in the country. It is expected by the year 2025, Amazon India will run all its operations with the aid of complete renewable energy.

Puga Geothermal Energy Project

The project is located in the Union Territory of Ladakh in India, where it utilizes geothermal resources comprising rivers as well as hot springs, to find the country's 1st geothermal power plant. It is expected that this project will be able to meet the electricity demand of the surrounding areas.

Bhadla Solar Park

The project is present in the Jodhpur district of the Rajasthan state in India, where the land is barren and receives plentiful solar radiation. The construction of this project started around the middle of the year 2015 and by the latter half of the year 2018, the 1st phase of the project was commissioned.

Jaisalmer Wind Park

The project was developed by Suzlon Energy, and it is considered the 2nd largest onshore wind project in India. It is also counted as the 4th largest onshore operational wind farm in the world. The mentioned Wind Park is present in the Jaisalmer district of the Rajasthan state in India.

Rewa Solar Project

In the Gurh Tehsil of the Madhya Pradesh state of India, Rewa Ultra Mega Solar Limited developed this project and by the middle of 2018, the project was commissioned. The project claimsto have a capacity of 759 MW and the generated electricity is to be supplied to Indian Railways.

Muppandal Wind Farm

The Muppandal Wind Farm is present in the state of Tamil Nadu in India, and it is considered to be the largest wind farm in the country. In the year 2007, it was developed by the Tamil Nadu Energy Development Agency, and it claims to have a capacity of 25.5 MW, which also shows the country's extraordinary progress in transitioning from non-renewable energy to Green Energy.

7 Methodology

In this section, some major problems that were noticed during the course of the earlier-mentioned projects, are the following:

Green Energy Corridor: The coordination between the Indian states was a major challenge during Phase 1 of the project. Then, the pandemic also slowed down the project and brought related problems like scarcity of labor force and so on.

Amazon's Wind and Solar Projects: Technological challenges and transportation issues to remote locations like Osmanabad would be the major problems faced in such large-scale innovative projects.

Puga Geothermal Energy Project: During the course of this project, the geothermal fluid that was supposed to be pumped back underground after extracting the heat, the Puga Stream was affected due to its unexpected flow. Lack of experience and difficult terrain as well as challenging situations in the location of the project created obstacles in the development of the project. Of course, concern for the environment along with the negative effects on the birds and wild animals were also major concerns to overcome.

Bhadla Solar Park: The scale as well as the location of the project were major challenges faced to complete the project, as it was also noticed that there were frequent sandstorms apart from the dust storms on site. Then, the output as well as efficiency of the solar panels were affected due to the accumulation of dust over them.

Rewa Solar Project: Financing such a large-scale project was a major hurdle as it was required to follow international standards to structure the balancing of risk allocation. Also, it needed to satisfy the conditions to get a loan from the World Bank. However, problems like groundwater concern in and around the site were a major concern, in addition to the damage caused by the heavy rains in the year 2019 to the project. Well, local employment is still not up to the mark in reality as it was promised at the beginning of the project.

Jaisalmer Wind Park: The major Challenge observed in the Jaisalmer Wind Park project was the environmental issues, which caused protests from the villagers.

Muppandal Wind Farm: The project caused a decline in agriculture and land, which made the local farmers have mixed reactions about the operation of the project, despite having the job generation for the locals.

8 Results and Discussion

In this section, data from different sources were collected to perform graphical analyses:

Table 1: Plans for renewable energy (Source: IEA)

Renewable Energy Plans	MW
China in 2022	160,000
India's plan in 2023	50,000
India's plan for 2030	500,000
European Union in 2022	50,000

Table 2: Market growth of renewable energy (Source: IEA)

Renewable Energy Market Growth	In MW
PV Utility in 2017	63,000
PV Distributed in 2017	35,000
Hydropower in 2017	24,500
Onshore Wind in 2017	43,700
Offshore Wind in 2017	3,800
Bioenergy in 2017	6,400
Expected PV Utility in 2024	191,300
Expected PV Distributed in 2024	167,800
Expected Hydropower in 2024	28,100
Expected Onshore Wind in 2024	119,500
Expected Offshore Wind in 2024	21,700
Expected Bioenergy in 2024	11,000

Table 3: Modern bioenergy's share (Source: IEA)

Share of Modern Bioenergy Towards NZE	In (%)
Modern Bioenergy Share in 2010 towards NZE	5.6
Expected Bioenergy Share by 2030 towards NZE	13.1

Table 4: Major Renewable sources of energy's share (Source: IEA)

Share of Wind, Geothermal, Solar, Ocean, and Hydro Energies Towards NZE	**In (%)**
Wind, Geothermal, Solar, Ocean, and Hydro Energies in 2010	3.1
Wind, Geothermal, Solar, Ocean, and Hydro Energies in 2030	17.4

Table 5: Major or top Countries with high production of renewable energy (%) (Source: Wisevoter)

Countries	**Renewable Energy Production (%)**
Iceland	86.87
Brazil	46.22
UK	17.95
USA	10.66
India	9.31
China	14.95
Sri Lanka	21.4

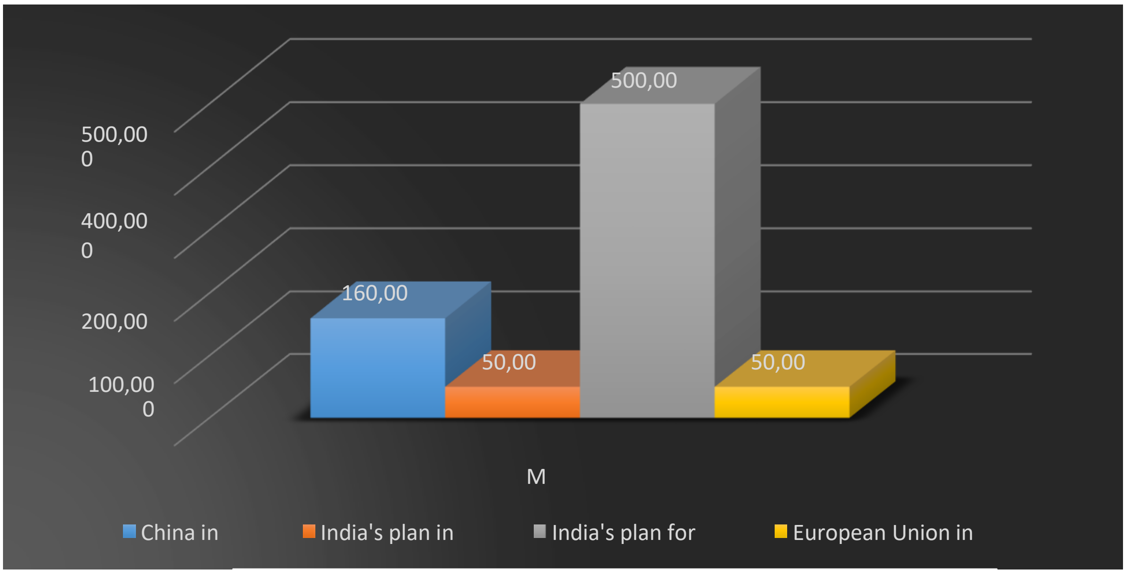

Figure 1: Plans for renewable energy (Source: IEA).

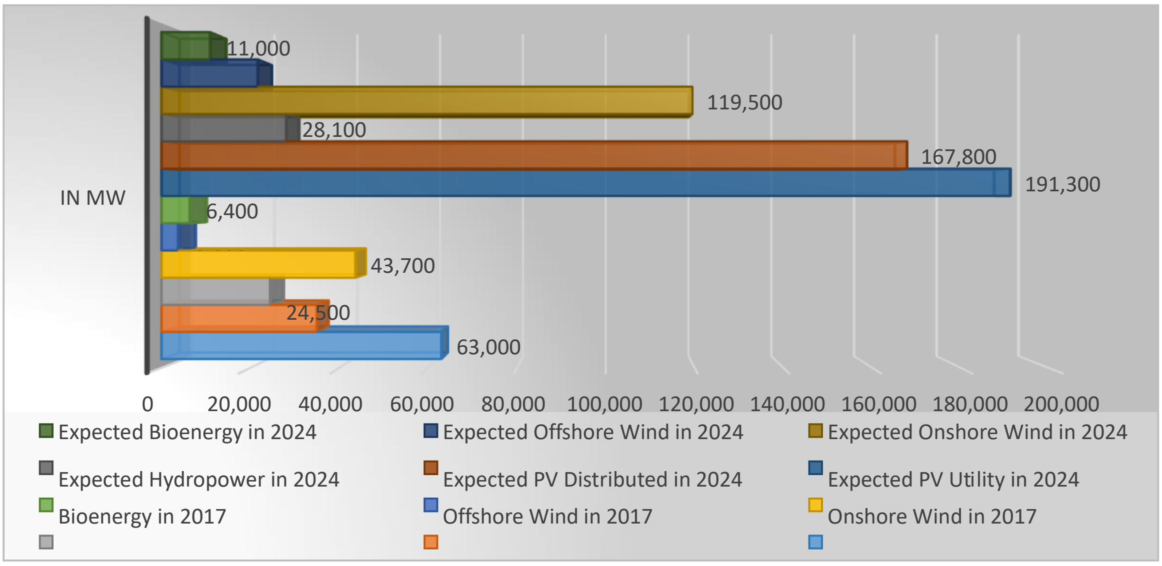

Figure 2: Market growth of renewable energy (Source: IEA).

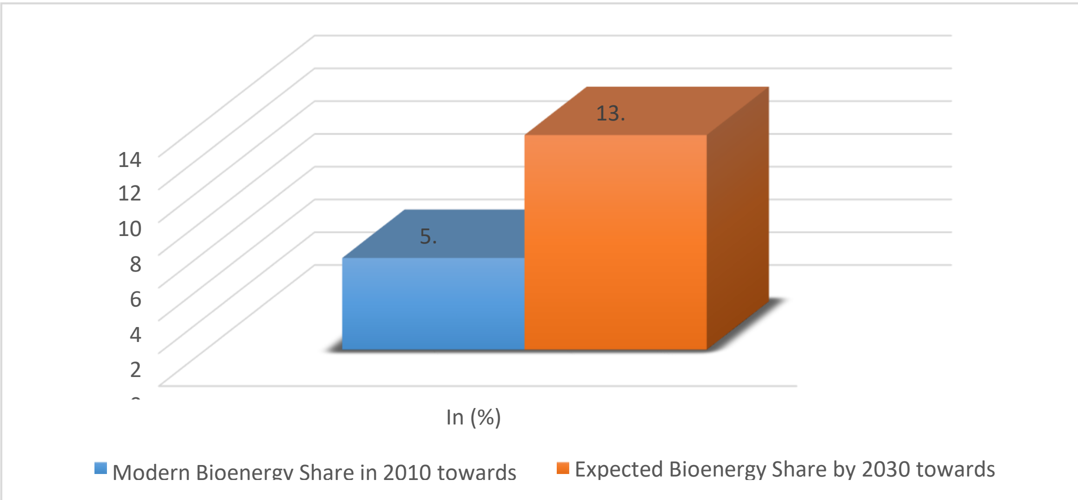

Figure 3: Modern bioenergy's share (Source: IEA).

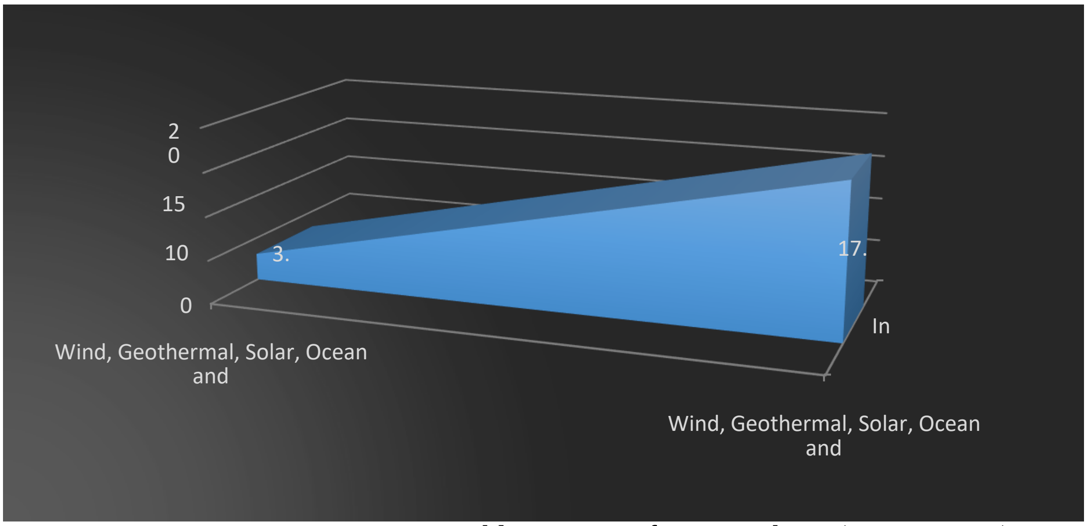

Figure 4: Major Renewable sources of energy share (Source: IEA).

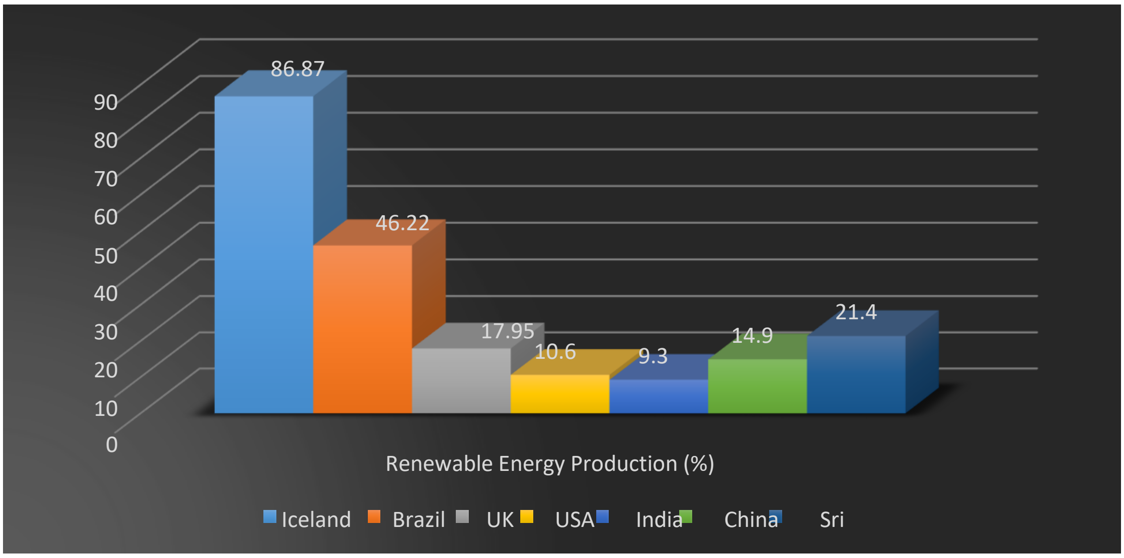

Figure 5: Major or top Countries with high production of renewable energy (%) (Source: Wisevoter).

8.1 Major Advantages and Challenges of Green Energy

In this subsection, based on the above graphs, the focus was given to analyzing the numerous advantages as well as challenges:

- According to Fig. 1, the plan for Green Energy in China in the year 2022 was even higher than European Union and India, but India's long-term plan till 2030 is a big one and after completing the scheduled plan in the coming seven years, there will be a major change in the country's effort to reduce its carbon footprint and towards the path of sustainable development.
- According to Fig. 2, the market for renewable energy has been growing rapidly in recent years, which will help in the development of green energy. It is safe to say that it will be a wise choice to invest further in green energy in the future. However, PV Utility as well as PV Distributed are expected to dominate the market.
- Based on Fig. 3, it can be seen that the market share of modern bioenergy is expected to rise from 5.6% in the year 2010 to 13.1% by the year 2030, towards the plan for Net Zero Energy, which means that the modern bioenergy will have more than double

of its share in the span of twenty years. This also shows the future increasing demand for modern bioenergy.

- According to Fig. 4, the share of Wind, Geothermal, Solar, Ocean, and Hydro Energies rose from 3.1% in the year 2010 to 17.4% by the year 2030, indicating that these renewable sources of energy are expected to have an increased share of over 5 times towards the plan for Net Zero Energy in the span of two decades. This also shows the importance and demand of these sources of energy. It is also safe to say that Green Energy will have a bright future based on the high future demand for these sources of energy.
- Based on Fig. 5, Iceland dominates the world with the highest % of renewable energy production but developing countries like Brazil and Sri Lanka are producing a higher % of renewable energy than developed and advanced countries like the UK. Similarly, China which is a developing country is also focusing more on producing renewable energythan advanced countries like the USA. India is not that far from developed countries like the USA in % of producing renewable energy, so India's progress in the development of green energy is good after taking into consideration that India became the world's most populated country in the 1st half of the year 2023 also increasing the demand for more energy.
- According to Fig. 5, it is safe to say that for India to match the % of the production of renewable energy with the top countries in the world, it will be a big challenge with the growing population and demand for more energy along with a technological challenge to make the whole country rely on green energy in the future.

9 Conclusion

This paper explains the concept of green energy and how it is important in the current times. The paper also covered the types of green energy briefly as well and several published research studies were considered to find out the gap in the recent research. Numerous major projects were discussed and the main challenges that were faced in the course of those green projects were talked about. The main focus was given on India and its current stand as well as policies in support of green energy in this study. Some graphical analyses were performed to support the study further. India's long-term plan till 2030 is a big one and after completing the scheduled plan in the coming seven years, there will be a major change in the country's effort to reduce its carbon footprint and towards the path of sustainable development. India to match the % of production of renewable energy with the top countries in the world, will be a big challenge with the growing population and demand for more energy along with technological challenges to make the whole country rely on green energy in the future. Then, many contractors, people, and companies still don't understand the importance of green energy projects as they think that at present things are already fine for them with conventional non-renewable projects. Lack of awareness is still there, along with people who are inflexible and do not consider future problems, which are causing hindrances in the development of green energy projects. Also, green projects are not producing the anticipated amount of employment in reality and inconsistent amount of employment, which are also major hurdles to overcome.

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RESETTLEMENT STRATEGIES AND SUSTAINABLE DEVELOPMENT: A CASE STUDY OF THE MORAGOLLA HYDROPOWER PROJECT

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Abstract: This paper, titled "Resettlement Strategies and Sustainable Development: A Case Study of the Moragolla Hydropower Project," explores the comprehensive approach taken by the project to address resettlement challenges and foster sustainable development. The Moragolla Hydropower Project (MHP), a key component of the Sri Lanka: Green Power Development and Energy Efficiency Improvement Investment Program, exemplifies how large-scale infrastructure projects can promote sustainability and social well-being. MHP's Entitlement Policy, encompassing the Resettlement Plan (RP), extends beyond compensation, emphasizing a Community Development Plan that uplifts household income, education, and social cohesion. Special focus is placed on empowering women and children through skill development and gender-specific training. The establishment of a Grievance Redress Mechanism (GRM) ensures transparency and dispute resolution, while dual monitoring mechanisms uphold accountability in the RP's execution. MHP stands as a model for responsible and sustainable development, emphasizing holistic well-being and sustainability, in alignment with the United Nations Sustainable Development Goals (SDGs). This case study of the Moragolla Hydropower Project illustrates a path forward for large-scale projects, demonstrating how they can contribute to both sustainable development and the welfare of affected individuals.

Keywords: Resettlement Strategies; Hydropower Project; Sustainable Development; Grievance Redress Mechanism; Socio-Economic Impacts

1. Introduction

The Moragolla Hydropower Project (MHP) represents a pivotal initiative within the broader Sri Lanka: Green Power Development and Energy Efficiency Improvement Investment Program, financed through the Multi-tranche Financing Facility of the Asian Development Bank (ADB). Under this program, Tranche-1 encompasses two critical components, namely Generation and Transmission-Distribution, which collectively address Sri Lanka's growing energy demands while embracing a more sustainable approach.

As is typical for development projects of this scale, the Moragolla Hydropower Project brings forth both economic and social considerations that must be addressed throughout its implementation. To comprehensively evaluate and mitigate these impacts, a detailed Census Survey was conducted. This survey illuminated the multifaceted effects, including those on residential homes, economic livelihoods, and social dynamics within the project's footprint. To minimize these consequences, the project underwent design alterations and introduced various measures. Additionally, an extensive study was conducted to delve deeper into the socio-economic implications of the project.

In response to the findings of the Census Survey and the additional socio-economic study, an Entitlement Policy was formulated. The overarching objective of this policy is to safeguard the rights and livelihoods of those affected by the project, with an emphasis on improving their socio-economic well-being. This commitment is expounded upon in the Resettlement Plan (RP), which outlines measures to enhance living standards and the general well-being of the affected population. Special provisions have been incorporated in the RP to cater to vulnerable groups, ensuring that their unique needs are addressed.

The heart of the RP extends to more than just compensation; it includes an ambitious Community Development Plan aimed at bolstering household income, promoting education, and fostering social cohesion. Specifically, it lays out initiatives targeting women and children to empower them through skill development and gender-specific training programs.

Furthermore, the RP incorporates a Grievance Redress Mechanism, offering an avenue for transparently addressing any concerns or disputes that may arise during the implementation of the project. The commitment to successful implementation and the welfare of the affected population is underscored by a dual monitoring mechanism. Internal monitoring is conducted periodically by the executing agency, while an independent external monitor, appointed for the RP's oversight, provides reports to the executing agency at regular intervals.

In sum, the overarching goal of the Resettlement Plan is to ensure that the affected people not only receive fair compensation but also experience an improvement in their socio-economic status. It is a commitment to enhance their quality of life and foster sustainable development, resonating with the aspirations of the donor agency, the executing agency, and, most importantly, the affected individuals.

2. Literature Review

Hydropower projects, particularly in emerging economies, play a crucial role in advancing sustainable energy generation, thereby aligning with broader sustainable development goals (World Bank, 2019). The development of such projects has grown in importance as a means to reduce greenhouse gas emissions and limit dependence on fossil fuels. Resettlement remains an integral concern in many hydropower projects, as the construction of dams and reservoirs often leads to the displacement of local communities (Khadka et al., 2018). Research in this domain underscores the socio-economic challenges faced by displaced populations and the need for effective resettlement strategies.

Resettlement policies, like the Entitlement Policy of the Moragolla Hydropower Project, aim to address the socio-economic impacts of displacement. These policies are designed to improve the socio-economic status of affected communities by providing compensation packages and support for rehabilitation (IUCN, 2020). Ensuring the well-being and livelihoods of the displaced populations is a fundamental objective of these policies.

Community Development Plans, a key component of many hydropower resettlement initiatives, are designed to bolster household income, promote education, and enhance social activities (World Bank, 2015). These plans serve to empower affected communities and enhance their overall quality of life. To address any grievances or conflicts that may arise during the resettlement process, many hydropower projects, including the Moragolla Hydropower Project, establish Grievance Redress Mechanisms (GRMs) (ADB, 2019). GRMs provide a transparent avenue for individuals and communities to voice their concerns and seek resolution. Successful implementation of resettlement plans relies on rigorous monitoring and evaluation. Internal and external monitoring processes ensure that policies are effectively executed, grievances are addressed, and outcomes align with the intended objectives (Cernea & Mathur, 2008).

3. Methodology

The development of criteria for the resettlement program involved a meticulous and comprehensive process, drawing upon key foundational documents such as the National Involuntary Resettlement Framework (NIRF) and the Resettlement Action Plan (RAP), which are administered by both the Asian Development Bank (ADB) and the Central Electricity Board (CEB). The initial planning phase was pivotal, encompassing the identification, management, and mitigation of risks associated with the resettlement process. The criteria, established in March 2014 by the CEB, played a central role in shaping the guidelines and standards for assessing the resettlement program's effectiveness. These criteria likely served as a benchmark, ensuring alignment with the overarching goals outlined in the National Involuntary Resettlement Plan. Furthermore, the integration of internationally recognized Hydropower Sustainability Tools underscored a commitment to a holistic and sustainable approach, bringing in global best practices and benchmarks to inform the design and execution of the resettlement program. The convergence of these elements in the criteria development process reflects a conscientious effort to address the multifaceted challenges associated with involuntary resettlement while adhering to rigorous national and international standards.

The data collection process involved field surveys, interviews, focus group discussions, and secondary sources. This helped in understanding the needs and concerns of the affected communities. The actual implementation of the resettlement plan included the construction of new housing and infrastructure, provision of amenities, and ensuring minimal disruption to the lives of the affected people. Measures were taken to support the resettled individuals and communities after the move. This included livelihood restoration, social integration, and ongoing support mechanisms. The effectiveness of the resettlement program was monitored and evaluated using key performance indicators, data collection methods, and the outcomes of the evaluation process. A grievance redress mechanism was established for the project. The status of the grievances received and resolved was monitored and addressed. The stakeholder engagement process involved consultations with various groups and individuals. The key concerns and expectations of the stakeholders were identified, and measures were taken to address them.

To ensure a systematic and fair process for identifying and assessing the resettlement needs of affected people (APs) and selecting houses or land for resettlement, the following methodology is employed:

1. Initial Impact Assessment:

- The resettlement process begins with an initial impact assessment conducted by a multidisciplinary team. This assessment identifies the potential impacts of the project on local communities, including APs, and determines the extent of displacement.

2. Baseline Data Collection:

- A comprehensive baseline data collection is carried out to gather information about the current living conditions, assets, and livelihoods of the APs. This data includes property ownership, land use, and socio-economic details.

3. Consultation and Participation:

- Community consultations are conducted to engage with the APs and gather their input. These consultations allow APs to express their preferences, concerns, and special needs regarding resettlement. The input of APs is integrated into the decision-making process to the extent feasible.

4. Criteria for Selection:

- The criteria used for the selection of houses or land for resettlement take into account the following factors:
    - **Proximity to the Project Site:** Preference is given to locations that are as close as possible to the APs' current residences to minimize disruption to their daily lives and livelihoods.
    - **Suitability for Livelihoods:** Resettlement sites are chosen based on their suitability for the APs' livelihoods, ensuring that they can continue their economic activities with minimal interruption.
    - **Access to Essential Services:** Locations with access to basic services such as healthcare, education, and clean water are prioritized to ensure the well-being of the APs.
    - **Community and Social Factors:** The social and community ties of the APs are considered to maintain their support networks and prevent social disruption.

5. Inventory of Losses (IOL):

- An inventory of losses (IOL) is prepared for each AP to assess the scope and value of the losses they will incur due to the project. This inventory serves as a foundation for determining compensation and benefits.

6. Identity Numbers and Files:

- Each AP is assigned a unique identity number, and a dedicated file is created for them. These files contain details of losses, entitlements, preferences, and special needs, ensuring a comprehensive record of each AP's situation.

7. Compensation Method:

- Compensation is provided in line with the provisions of the Land Acquisition Act (LAA) and is based on the replacement cost. In-kind compensation is preferred where feasible, but cash compensation is employed when necessary.

8. Timing of Resettlement:

- Resettlement of affected households occurs before the construction of the reservoir or project components. This timing ensures that APs are relocated to suitable alternative locations before their current residences are affected by construction activities.

9. Constant Monitoring:

- A rigorous monitoring and evaluation system is established to prevent cost overruns and time overruns in the resettlement program. Continuous monitoring ensures that the process is executed efficiently and effectively, with adjustments made as needed.

4. Case Study

The Moragolla Hydropower Project, situated in a predominantly rural agricultural setting, necessitates comprehensive resettlement strategies to mitigate the social and economic impacts on the affected people (APs). The project area is characterized by homestead gardens, mixed cultivations, and tea plantations as a source of income for some APs. Our objective is to ensure that the resettlement process is executed efficiently, and that APs are treated fairly during this transitional phase.

The Entitlement Matrix: One of the key components of our approach is the development of an Entitlement Matrix. This matrix, outlined in Table No. 01, serves as a comprehensive guideline that determines the entitlements, compensations, and benefits for APs affected by the project. It encompasses the different categories of impacts, including residential houses, land, structures, agricultural lands, and more. The matrix defines the specific measures and compensation levels provided to the APs in each category. The Entitlement Matrix was carefully designed to address the unique needs and circumstances of the affected people.

Table 1: The Entitlement Matrix

	Nature/ Type of Loss	Application	Definition of Entitled Person	Entitlements
1	Loss of residential house	Residential houses in the project-affected area existed as of the cut-off date	a) Owner with legal right b) Non-titled dweller c) Encroacher as at the cut-off date	a) House for a house with more space and facilities decided by CEB will be provided based on the floor area of the affected house, built on land not less than 15 perches in extent. b) The alternative houses will be constructed in the following types based on the floor area of the affected houses. • Type A –for floor area less than 650ft^2 • Type B –for floor area greater than 650ft^2 and less than750 ft^2 • Type C – for floor area greater than 750 ft^2 and less than 950 ft^2 • Type D –for floor area greater than 950 ft^2 and less than 1100ft^2 • Type E – for floor area greater than 1100ft^2 and less than1360ft^2 • Type SP – for floor area greater than 1360ft^2 and less than 1800ft^2 c) If a Project-affected person is willing to construct his house by himself according to the design prepared by the project. Arrangements will be made to release funds through the Divisional Secretary in stages based on the progress of the construction. d) In the case where the residential land is over 0.25 acres and less than one acre, an alterna-

	Nature/ Type of Loss	Application	Definition of Entitled Person	Entitlements
				tive land of a similar extent including the extent of land on which the alternative house is built will be provided. If an alternative land cannot be provided due to scarcity of suitable lands, cash compensation based on the valuation determined by the Valuation department will be paid for the lands for which legal possession can be established. e) In the case where the land in which the affected house is located is over 15 perches but less than 0.25 acres or more than one acre, cash compensation in respect of the land over 15 perches or over one acre will be paid based on the valuation by the Valuation Department for which legal possession can be established. f) Encroachers on the state land will be entitled only to compensation to meet the cost incurred for the development of the excess land. g) In the case where an alternative house cannot be provided due to unavoidable circumstances, compensation based on replacement cost will be paid. h) Households residing in rented houses will not be entitled to alternative houses. However, they will be entitled to an ex-gratia payment not exceeding Rs. 90,000 /= paid only once. i) Shifting allowance up to a maximum of Rs. 50,000/= or transportation of goods and materials will be provided by the Project. j) Subsistence allowance of Rs. 30,000/= will be paid for the first month upon resettlement.
1.1	Business Places	Business Places affected by the project existed as of the cut-off date	a) Owner with legal right b) Non-titled business owners	a) An alternative business place will be provided with improved facilities at a suitable location. b) In the case where the land in which the affected business place is located is more than the land on which the alternative business place will be constructed, cash compensation in respect of the market value for the excess land will be paid based on the valuation determined by the Valuation department if the legal possession for the land can be established. c) If an alternative business place cannot be provided before the removal of the affected building, a temporary place to carry out the business will be provided by the project or a cash payment will be made, to rent a suitable place to continue with the business. d) Any loss of business income that occurred during the interim period will be compensated by the project subject to a maximum of three months based on the average income of the preceding three months.

	Nature/ Type of Loss	Application	Definition of Entitled Person	Entitlements
				e) Transport of goods and materials will be attended to by the project or a cash payment depending on the volume of goods and materials to be transported will be paid to the owner for the purpose. f) Those who are running businesses in rented buildings will not be entitled to alternative business places. However, they will be entitled to an ex-gratia payment not exceeding Rs. 90,000/=paid only once.
1.2	Loss of Informal Business	Informal Business Affected by the Project	Owner of the Informal Business	Once and for all payment (an income restoration allowance) of Rs. 40,000/= to rebuild the informal business.
2.0	Agriculture Land	Land situated in the project-affected area	a) Owner with legal right b) Government land (permit holder) c) Non-titled dweller d) Encroachers into the state land before cut- off off-date	a) An alternative agricultural land similar to the extent of the land to be acquired will be given, at a suitable location or b) Cash compensation based on the valuation determined by the Valuation Department will be provided. c) Alternative land will be prepared by the project to suit the anticipated cultivation, or a cash payment will be made for the purpose. d) Once and for all cash payment will be made to purchase seeds and fertilizer. e) Encroachers who have abandoned the agricultural activity will not be entitled to alternative agricultural land. f) In case where, alternative land cannot be provided due to scarcity of suitable lands, cash compensation based on the valuation determined by the Valuation Department will be paid for the lands for which legal possession can be established. g) If there is a time lag between the allocation of alternative agricultural land and taking over of the land for the project, cash compensation for loss of income subject to a maximum of three years will be paid to the cultivator based on assessment obtained from the relevant Divisional Secretary. h) Those who are without legal rights will be entitled only to the development cost of the land. i) Agricultural extension services to increase productivity in collaboration with the Agriculture Department will be organized.
2.1	Commercial Agriculture (Tea, Rubber, etc.)	Land situated in the project area	a) Owner with legal rights b) Non-title holders c) Encroachers into the state land before cut- off off-date	a) If the affected land does not exceed one acre or not less than 0.25 acre alternative land to a similar extent will be provided by the Project. b) Where the lands to be acquired are larger than one acre or less than 0.25 acre, cash compensation in respect of such lands will be paid based on the valuation determined by the Valuation Department, provided that

	Nature/ Type of Loss	Application	Definition of Entitled Person	Entitlements
				legal ownership is established. c) Alternative land will be prepared by the project to suit the anticipated cultivation or a cash payment will be made for the purpose. d) Once and for all cash payment will be made to purchase seeds and fertilizer. e) In cases where, alternative lands cannot be provided due to scarcity of suitable lands, cash compensation based on the valuation determined by the Valuation Department will be paid for lands for which legal possession can be established. f) If there is a time lag between the allocation of alternative agricultural land and taking over of the land for the project, cash compensation for loss of income subject to a maximum of three years will be paid to the cultivator based on assessment obtained from the relevant Divisional Secretary. g) Encroachers who have abandoned the agricultural activity will not be entitled to alternative agricultural land. h) Those who cannot establish legal ownership or encroachers into state lands will be entitled only to the development cost of the land.
2.2	Other Lands	Affected (Acquired) by the project	Owners with legal rights	Compensation based on the valuation determined by the Valuation Department will be paid.
3.0	Loss of standing trees and perennial crops	Trees and perennial crops affected by the project	People who own the land in which the trees and perennial crops exist	Cash compensation determined by the Valuation Department will be paid (in determining the compensation; type, age, and productivity of the trees and perennial crops will be taken into consideration).
4.0	a) Special needs of vulnerable people. b) Female-headed without adult male support c) Differently able people d) Elderly (Householders over 60 years of age) e) Very poor families	Affected vulnerable groups of people requiring special assistance	All APs requiring special assistance	a) Special livelihood restoration programs will be organized. b) Preference will be given when allocating alternative houses. c) Special ex-gratia payment of Rs. 40,000/= will be paid only once.

	Nature/ Type of Loss	Application	Definition of Entitled Person	Entitlements
5.0	Common amenities	Common amenities affected due to the project	Local community	Replacement will be done at the earliest possible time.
6.0	Structures other than houses, business places, workshops, industries	Affected by the Project	Owners with legal rights	Cash compensation based on the replacement cost will be paid.
7.0	Public Utilities a) Water b) Electricity c) Telephone d) Drainage	Public utilities affected due to the project	Owners of the public utilities	Relocation of utilities will be done at the proper time.
8.0	Shrines and tombs	Affected by the project	Owners of the shrines and tombs	a) Relocation will be done by the project or b) Cash compensation will be paid for relocation.
9.0	Infrastructure a) Local roads b) Bridges c) Water points etc.	Affected by the project	Communities receiving benefits from the infrastructure	Restoration will be done by the project in consultation with affected communities.
10.	Loss of employment	People losing employment due to acquisition of properties and project activities	People who will lose wage employment in the private enterprises affected due to the acquisition of properties	An allowance not exceeding Rs. 20,000/= per month will be paid for the period of losing employment subject to a maximum of three months.
11.	a) Loss of livelihood (self-employment)	a) People losing livelihood as a result of displacement due to land acquisition for the project	a) People whose self-employment ventures will be disturbed	a) Once and for all allowance of Rs. 50,000/= will be paid to re-establish the livelihood.
	b) Loss of livelihood (Sand mining)	b) Sand mining locations affected by the Project	b) People who will lose income from sand mining	b) Assistance will be given for alternative sources of income opted for by the affected sand miners. c) Payment of cash compensation will be arranged for loss of income for the period from the date on which the sand mining will

	Nature/ Type of Loss	Application	Definition of Entitled Person	Entitlements
				be disturbed and the start of the new source of income, subject to a maximum of six (06) months as determined by the Divisional Secretary.
12	Loss of livestock husbandry	Places of livestock husbandry affected by the Project	People whose livestock husbandry activities are disturbed due to the Project	a) Provide alternative places for livestock husbandry with improved facilities. b) Will be provided extension services to improve the income from livestock husbandry.

The Assessment Process: A crucial aspect of the resettlement process involves a comprehensive assessment of the impacts on APs. This process begins with an initial impact assessment, which is conducted by a multidisciplinary team. The team considers a range of factors, such as proximity to the project site, suitability for livelihoods, access to essential services, and community and social factors. These criteria are systematically used to identify and assess the resettlement needs of APs.

Selection of Resettlement Options: Based on the assessment, APs are presented with various resettlement options tailored to their specific situations. The selection of resettlement options is influenced by the preferences and concerns expressed by the APs during community consultations. The overarching goal is to resettle APs in locations that minimize disruption to their daily lives and livelihoods. Options may include alternative housing, commercial establishments, and lands, all carefully considered to meet the unique needs of the APs. This methodology aims to ensure that the resettlement process is executed transparently and systematically, considering the well-being and livelihoods of the APs. The Entitlement Matrix, assessment process, and selection of resettlement options are integral components of our commitment to mitigating the social and economic impacts of the Moragolla Hydropower Project.

5. Results

5.1 Stakeholder Engagement Process

The Moragolla Hydropower Project was characterized by a robust stakeholder engagement process, recognizing the pivotal role of affected people and relevant stakeholders in shaping the project's success. Throughout the project's lifecycle, inclusive and interactive communication channels were established to facilitate an exchange of information, concerns, and valuable feedback.

Key stakeholders in this engagement process included:

- **Divisional Secretaries**: Actively participating in project discussions and decision-making.
- **Local Authorities**: Comprising Chairpersons and Council Members within the project area.
- **Government Agencies**: Representatives from District and Divisional level government bodies.
- **Grama Niladharies**: Serving as critical points of communication within the local community.
- **Farmer Organizations**: Operating under the Dunhinda Canal Irrigation Scheme, contributing local perspectives.
- **Ulapane Industrial Estate**: A relevant institution with stakes in the project.

- **Distinguished Community Members**: Providing valuable input based on their understanding of local dynamics.
- **Project Staff**: Facilitating communication and bridging the gap between the project and stakeholders.
- **Affected People**: The central focus, understanding their concerns, and informing them of their entitlements.

Engaging with these diverse stakeholders was pivotal to understanding the multifaceted issues arising from the project. Frequent stakeholder meetings and open dialogues fostered a cooperative environment where concerns could be addressed, and ideas could flourish. Stakeholder meetings also provided a platform for sharing project information, clarifying queries, and unveiling the project's potential benefits.

Additionally, the establishment of the Housing Committee played a vital role in facilitating communication with the affected people, as they were given a platform to express their views, raise concerns, and actively participate in resettlement planning. At the commencement of the project, a Housing Committee was formed to serve as an integral channel of interaction with affected people. This committee evolved to function not only as a means of information dissemination but also as a welfare society for the affected individuals. A pivotal development in this process was the establishment of the "Moragolla Village Welfare Society" in 2019, demonstrating an enduring commitment to the well-being and sustainable development of the affected community.

5.2 Grievance Redress Mechanism (GRM)

The establishment of a Grievance Redress Committee (GRC) was a proactive measure to address potential grievances stemming from involuntary resettlement. A well-defined GRM is essential for managing grievances during the resettlement planning and implementation stages. The GRC consisted of the following members:

- **Chairperson**: Mr. J C Ranepura, Additional District Secretary (Lands) of the Kandy District.
- **Members from the Affected Persons (AP)**: Ven. Bowala Wimaladhamma, P G Wijethunga, Ven. Mawathure Chandima, and K M AIllangakoon.
- **Secretary**: Eng N W Bulathge, Civil Engineer of the Project Management Office (PMO).

The GRM's primary goal was to provide affected people with a transparent and impartial platform to express their grievances and disputes. To ensure that affected people were well-informed about the GRM procedures, notices were published in national newspapers in Sinhala, Tamil, and English. Local communities were also informed through Grama Niladharies. The GRM received and addressed grievances brought forward during the reporting period. These grievances encompassed a range of issues, from damages resulting from project activities to concerns about the quality of services. The GRC meticulously reviewed each grievance and provided appropriate solutions to address the concerns raised by the affected individuals.

5.3 Outcomes and Impact

The robust stakeholder engagement process led to the development of a collaborative environment where concerns were heard and addressed in real time. Through frequent stakeholder meetings, valuable insights were gained and affected people were well-informed about their entitlements, fostering a sense of empowerment within the community. The establishment of the Housing Committee and the "Moragolla Village Welfare Society" further strengthened the connection between the project and the affected people, ensuring their well-being and sustainable development in the project area.

The effective implementation of the Grievance Redress Mechanism demonstrated the project's commitment to resolving grievances transparently and impartially. By addressing issues proactively, the project aims to build trust within the affected community. The combined results of the stakeholder engagement process and the Grievance Redress Mechanism underscore the project's dedication to responsible and sustainable development, with a strong focus on the well-being of the affected people and their local community.

6. Discussion

The Moragolla Hydropower Project (MHP) is a significant initiative within Sri Lanka: Green Power Development and Energy Efficiency Improvement Investment Program, financed by the Asian Development Bank (ADB). This project addresses the dual objectives of meeting Sri Lanka's growing energy demands and adopting a more sustainable approach. As is typical for large-scale development projects, it presents a complex landscape of economic and social considerations that require comprehensive assessment and mitigation. This discussion section analyzes and interprets the project's results, focusing on how it contributes to sustainable development while addressing the needs of the affected people (APs).

Resettlement and Socio-Economic Implications

Hydropower projects, as important contributors to sustainable energy generation, are vital components in the global transition toward reduced greenhouse gas emissions and reduced dependence on fossil fuels (World Bank, 2019). However, one common challenge associated with such projects is the displacement of local communities due to the construction of dams and reservoirs. Research highlights the socio-economic challenges faced by these displaced populations, emphasizing the need for effective resettlement strategies (Khadka et al., 2018).
The Entitlement Policy developed for the Moragolla Hydropower Project exemplifies a commitment to addressing the socio-economic impacts of displacement. By providing compensation packages and rehabilitation support, such policies aim to improve the socio-economic status of affected communities (IUCN, 2020). This project places a strong emphasis on safeguarding the rights and livelihoods of those affected, with the Resettlement Plan (RP) outlining measures to enhance living standards and general well-being. Importantly, the RP acknowledges and caters to the needs of vulnerable groups, ensuring that their unique challenges are considered.

Community Development for Sustainable Development

At the heart of the RP is not merely the provision of compensation, but an ambitious Community Development Plan designed to uplift household income, promote education, and foster social cohesion. By outlining initiatives aimed at empowering women and children through skill development and gender-specific training programs, this project recognizes the significance of gender equity in development. This approach contributes to the achievement of sustainable development goals by ensuring that the benefits extend to the entire community (World Bank, 2015).

Moreover, the RP introduces a Grievance Redress Mechanism (GRM) to address any concerns or disputes transparently. The GRM provides an essential avenue for individuals and communities to voice their concerns and seek resolutions. This mechanism is crucial in maintaining trust and transparency throughout the project's lifecycle (ADB, 2019).

Dual Monitoring for Accountability

The commitment to successful implementation and the welfare of the affected population is further underscored by a dual monitoring mechanism. Internal monitoring, conducted periodically by the executing agency, helps ensure the efficiency and effectiveness of the resettlement program. Simultaneously, an independent external monitor provides oversight and produces reports at regular intervals, enhancing accountability in the execution of the RP.

Promoting Sustainable Development and Well-Being

In summary, the overarching goal of the Resettlement Plan associated with the Moragolla Hydropower Project is to go beyond fair compensation; it strives to improve the socio-economic status of the affected population. This commitment echoes the aspirations of the donor agency, the executing agency, and, most crucially, the affected individuals. It aligns with the United Nations Sustainable Development Goals (SDGs) by recognizing that sustainable development encompasses both environmental and social dimensions. The RP is more than a compliance requirement; it is a practical demonstration of the project's dedication to the well-being and sustainable development of the affected people. The careful consideration of their unique needs, the provision of opportunities for growth and empowerment, the establishment of transparent grievance mechanisms, and rigorous monitoring collectively reflect a holistic approach to development.

As this project moves forward, it serves as a model for how large-scale infrastructure projects can promote sustainability and social well-being. By addressing not only the economic but also the social aspects of development, the Moragolla Hydropower Project provides a blueprint for creating a better future that serves the interests of all stakeholders involved.

7. Conclusion

Implementation of the Moragolla Hydropower Project now is at the construction stage and safeguarding compliance is an important and highly valued aspect. The beginning of project's social safeguard aspects started with a review of project background documents relating to resettlement and social safeguard issues. All elements were in place for enacting an efficient safeguard framework, implementing RP, and monitoring of social safeguard issues. Social safeguard and Resettlement monitoring usually are done by focusing on the scheduling of activities and details of compensation and payment status following the RP. Other monitoring indicators are also used, including direct one-on-one communications with APs by way of forming various committees, in connection to property valuation and compensation payment, outcomes of grievances and redresses of grievances, and overall physical progress of resettlement plan implementation in a specific context.

However, up to the reporting period, the land acquisition process is nearing completion, and construction of the resettlement village is completed. Since the land acquisition process had to be completed before all other activities of the Project, every effort had been made to expedite land acquisition. Possession of the Resettlement land and all of the lands for project component w It is observed that land acquisition can be expedited, by assigning additional staff in relevant government institutions involved in this process such as Divisional Secretaries (DS), Department of Survey and Valuation Department etc., where necessary and CEB has provided the relevant assistance and infrastructure facilities. Despite this, the Survey Department has assured us that they will give priority to completing the survey work, and at present the survey work has been completed satisfactorily. There was an early delay in getting the valuation reports from the Valuation Department, but with close coordination with the officials, the work has now been carried out satisfactorily.

A Grievance Redress Committee was appointed and the formation of the GRC was notified to the general public by publication of a notice in national newspapers. The local community was also informed about the grievance handling procedures of the project through Grama Niladharis of the area and displaying notices at important public places and also by having meetings with all the stakeholders including the PAPs. ere taken over by CEB.

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SUSTAINABLE SOLUTIONS

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BIO CHAR DERIVED FROM WASTE BIOMASS SOURCES AS A FILLER FOR NATURAL RUBBER: A REVIEW

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Abstract: Biochar (BCh) is a sustainable source of carbon that can be considered as charcoal derived by heating plant materials. Biochar characterized by its porous structure, high carbon content, wide particle size distribution, and surface functional groups made it a modern sustainable material in many engineering applications. Comparable properties of BCh with carbon black (CB) which is considered as the most versatile reinforcing filler in the rubber industry, have widened the spectrum of engineering applications of BCh towards achieving sustainable goals. Thus, the current review focuses on identifying BCh as a potential replacement for CB as a reinforcing filler for rubber matrices. It is noticeable that the physicochemical and mechanical properties of BCh are highly subjective to precursor plant source and processing methods. Nevertheless, it is interesting to note that BCh produced from several natural resources, i.e., sawdust, sugarcane bagasse, maize stover waste, coconut shell and coir waste, etc. show high carbon contents of >73 wt% while that of CB is 96 – 99.5 %. High carbon content is a favorable indicator for any reinforcing filler. Furthermore, the ash content and surface area of some BCh are closer to that of CB. Some sentences revealed that the surface functional groups found in BCh are almost similar to the functional groups of CBs (such as -COOH, phenolic, -OH, amine, amide, and laconic) which enhance the reinforcing nature of in elastomeric matrix. Moreover, the fully and partially filled BCh-rubber compounds show analogous and sometimes superior mechanical properties to that of CB-rubber compounds which clarifies BCh as a prospective filler for the rubber industry.

Keywords: Biochar; Natural Rubber; Sustainability; Waste Biomass; Carbon Black; Filler

1. Introduction

BCh is a carbon-rich material that is produced by heating organic materials to higher temperatures in the absence of oxygen (Lay et al., 2020). Literature evidence number of research conducted to produce BCh from natural biomass sources which are lignocellulosic and some non-lignocellulosic such as dairy manure, sewage sludge, etc (Greenough et al., 2021). Among them, this sustainable carbon source can be derived from many waste biomass sources such as wood residues (Wijitkosum, 2022), coconut shells (Jong et al., 2014), tea waste (Iresha et al., 2016), etc. Those BCh exhibit valuable properties of carbon content in the range of 60 – 90 % (McGlashan et al., 2012), surface area ranging from 8 m^2/g to 132 m^2/g and pore volume range of 0.016 cm^3/g to 0.083 cm^3/g (Leng et al., 2021). These are advantageous factors for the application of soil amendment (Al-Wabel et al., 2015), carbon sequestration (Hansen et al., 2016), and water purification (Siipola et al., 2020). However, such properties are subjective to the type of biomass and pyrolyzing conditions (Santos et al., 2019). This inconsistency of properties of waste-based BCh limits the engineering applications of this sustainable and renewable material. Yet, certain biochar exhibits comparable properties featuring high carbon content, low ash contents, and high porosity compared to conventional carbon sources (Greenough et al., 2021). Thus, optimization of pyrolysis conditions is possible for more uniform production of BCh, in terms of properties and yield which is another focus of BCh research.

Majorly, BCh production can be considered as an alternative to petroleum-based carbon products such as carbon black (CB) and activated carbon considering the adverse health and environmental effects caused during production and utilization (Fan et al., 2020). It is said that 2.5 kg of oil has to be burned to produce 1.0 kg of CB, commercially (Lay et al., 2020) which on the one hand is an extreme utilization of non-renewable petroleum products. Meanwhile, BCh production and burial are considered as negative carbon dioxide emissions which was estimated as BCh has the potential to offset the 9 % of carbon dioxide emissions in Europe (Glaser et al., 2009). Thus, BCh is undoubtedly a sustainable and renewable alternative for respective applications of CB.

With the favorable properties of BCh mentioned earlier, one major potential application of BCh is replacement as a rubber filler. CB is a carbon-rich filler material widely used for engineering applications nowadays, especially for manufacturing engineered rubber products like tires, bridge bearings, hoses, etc (Robertson & Hardman, 2021). CB with its high carbon content of> 90 %, low ash content of < 1.0 %, small particle size in the nanoscale, and the presence of favorable surface functional groups, excellent reinforcement is granted to rubber products (Fan et al., 2020; Gao et al., 2019; Greenough et al., 2021; Peterson & Kim, 2020). Therefore, the study of BCh as a filler for Natural Rubber (NR) is of paramount importance due to its potential to promote regeneration, sustainability, and cost-effectiveness. Thus, can advance to circular economy practices and reduce dependency on non-renewable resources.

With the background being stated, the current review will focus on waste biomass-based BCh and their suitability as a competitor to CB by analyzing the physical properties and chemical nature of BChs, and the mechanical properties of rubber compounds prepared by BCh replacement. In Sri Lanka, 12000 MT of tea waste (Sri Lanka Tea Board, 2021), 700,000 – 750,000 MT of coconut shell (Sri Lanka Business, 2021), 11,000,000 MT of rice husk (2019/ 2020) (Illankoon et al., 2022), 275,00 MT of sugarcane bagasse (Pelwatte Sugar Company, 2021) are some waste biomass sources generate, annually. Some research has been conducted to generate BCh from tea waste (Keerthanan et al., 2020), rice husks (Illankoon et al., 2023), cinnamon waste (Karthika et al., 2021), etc. mainly for adsorption applications. Iresha et al. in 2016 was reported tea-waste BCh as a filler for rubber compounding with similar mechanical properties compared to CB-filled natural rubber vulcanizates (Iresha et al., 2016). Yet, there is a high potential to develop and produce BCh in Sri Lanka as a valuable material. Therefore, Sri Lanka is a leading rubber product manufacturer, and this analysis would be timely worth opening up eyes to futuristic research on alternative sustainable fillers for rubber, in an era where the country must deeply focus on uplifting the economy more sustainably and economically.

2. Physical properties of Biochar

Fillers for rubber are one of the important components in rubber formulation mainly due to the reinforcing effect as well as to increase the volume while reducing the cost of the product. Their features such as smaller particle sizes, high porosity, and chemical structure of the filler including surface functional groups are largely accountable for the filler reinforcement. Therefore, as the prime step, comparison of such filler characteristic properties of BCh with conventional filler like CB would be interesting to understand BCh as a prospective filler for rubber.

2.1 Carbon and ash content.

Three key characteristics of carbon fillers directly contribute to their reinforcement of the rubber matrix. Those are high carbon content, low ash content, and small particle size (Peterson & Kim, 2020). High carbon content is important for reinforcing fillers, especially CB because carbon particle is the functioning element in the CB which contributes to the reinforcing reaction. Therefore, the higher the carbon percentage, the higher the strength of the compound. Low ash content is another factor to be considered since biochar with high ash content reduces the reinforcing properties (Greenough et al., 2021). Another major characteristic is small particle size because large size particles build up localized stresses in the rubber matrix leading to failure (Abbas et al., 2019). Besides, smaller particles are easily dispersed through the rubber matrix making a more uniform distribution filler result in enhanced reinforcement. Therefore, analyzing BCh characteristics gives a clear link to conclude its suitability as a prospective filler for rubber.

Table 1 summarizes carbon content and ash contents for different BChs produced under different pyrolysis conditions. There, properties of BCh hugely swing depending on the BCh origin as well as the pyrolyzing conditions. As mentioned by Peterson and Kim in 2020, if BCh needs to be replaced with CB, the purity of BCh should reach the purity of CB which means carbon content reaches 100 % while ash content goes to 0 % (Peterson & Kim, 2020). Here, a close examination of those values suggests high carbon content in BCh produced from waste biomass sources such as tea waste, sawdust, sugarcane bagasse, maize stover waste, coconut shell, and coir waste where those values represent carbon values > 73 %. Interestingly, the ash content of those mentioned BCh samples was also recorded at lower values which are < 5 %. Further, the carbon content was enhanced in some BChs prepared at higher pyrolyzing temperatures. As an example, eucalyptus sawdust with 78.6 % carbon was improved to 90.9 % carbon when the pyrolyzing temperature was increased from 450 ^{0}C to 750 ^{0}C. But the ash content was also increased with increased pyrolyzing temperature which is another factor to consider when developing BCh as a sustainable future material for engineering applications. Not only the temperature but the heating rate and holding time during pyrolyzing are also important in optimizing BCh's physical properties. These facts emphasize the producibility of BCh and the ability to optimize or modify BChs as a usable product. Thus, BCh as CB replacement is worth analyzing further with this initial spotlight.

Table 1: Summary of BCh derived from different sources and their pyrolyzing temperature and corresponding carbon content and ash contents

Type of Biochar	Pyrolyzing temperature	Elemental Carbon (%)	Ash content (%)	References
Carbon black	-	96.0-99.5	<1.00	(Greenough et al., 2021)
Dairy manure	350	55.8	24.2	
	700	56.7	39.5	
Eucalyptus Sawdust	450	78.6	0.70	
	750	90.9	1.10	
Sugarcane Bagasse	450	81.6	2.10	
	750	90.5	2.20	
Coffee Husk	350	60.5	12.9	
	450	61.3	12.9	
	750	63.7	19.6	
Rice Husk	300	47.7	13.6	
	500	49.1	18	
	700	50.6	39.2	
Rice Straw	300	44.7		
	500	44.4		
	700	44.9		
Wheat Straw	450	64.8	8.2	
Pine bark	350	67.6	8.3	
	450	75.2	7.9	
	750	86.3	14.5	
Pine Wood	450	75.5	3.5	
Tea waste	300	63.51	3.81	(Mayakaduwa et al., 2016)
	500	68.07	8.45	
	700	73.63	12.84	
Cinnamon	700	79.88		(Karthika et al., 2021)
Paulownia		95.15±0.67	2.52	(Peterson, 2020)
Popular		89.07±4.39	1.97	
Coconut Shell		82.08	3.0	(Jong et al., 2014)
Waste wood pellets		83.63	11.1	
Maize stover		83.0	2.425	(Shenbagavalli & Mahimairaja, 2012)
Coir waste		76	1.96	

2.2 Surface area and particle size

Another important feature of filler are high surface area and smaller particle size for better reinforcement in rubber compounding. As shown in Table 2, the BET surface area of CB grades varies from 50 – 213 m^2/ g with their particle size which is in the nanoscale (Cho et al., 2004). When comparing BCh from waste biomass sources, the surface area of many BCh is not as high as CB at lower processing temperatures. However, when the pyrolysis temperature increased, the surface area exceeded the surface area of CB in different grades as given in Table 2 for some BCh such as Rice husk, Sugarcane bagasse, and pine sawdust. However, the particle size of the BCh is considerably higher than that of CB. As mentioned by Liu et al. in 2018, the initial grain size of BCh was in mm scale. When the BCh were processed via ball milling, the grains were reduced to ultrafine particles with their particle size turned to nanoscale while the surface area was improved drastically (Lyu et al., 2018). Here, the most emphasized fact is, that for BCh which is satisfied with higher carbon content and lower ash contents, there is a possibility to modify the BCh particle size and surface area to the comparable level of CB. Since it is difficult to find all properties in one BCh at first, optimization of pyrolysis conditions, post-processing, and treatments is important to develop the most complying BCh replacement for CB.

Table 2: BET surface area of CB and BChs derived from different biomass at different pyrolyzing temperatures

Carbon Black type	Particle size	BET surface area (m^2/g)	Reference
Thermal Black	40 – 200 nm	50 – 120	(Cho et al., 2004)
Furnace Black	20 – 30 nm	100 – 200	
Plasma carbon black	20 – 30 nm	213.23	
Biochar Type	**Pyrolyzing Temperature (^0C)**	**BET surface area (m^2/g)**	**Reference**
Sewage Sludge	250	0.8	(Greenough et al., 2021)
	550	12.8	
Dairy Manure	350	1.64	
	700	187	
Rice Husk	350	11.6	
	650	281	
Pine Sawdust	350	3.39	
	450	100	
	550	432	
	650	444	
Sugarcane Bagasse	450	51	(Lyu et al., 2018)
	600	359	
Coconut Shell		374	(Jong et al., 2014)
Tea waste	300	2.28	(Mayakaduwa et al., 2016)
	500	1.57	
	700	342.2	

2.3 Biochar structure and surface functional groups

The structure of CB is mainly a mixture of amorphous and crystalline forms of carbon where the ratio of amorphous and crystalline regions differed based on the CB grade. Normally, the crystalline portion changes proportional to the particle size means CB grades with higher particle size contain a more crystalline structure (Greenough et al., 2021). Further, the presence of functional groups on the CB surface such as phenolic, -COOH, -OH, carbonyl, lactic, ether, ester, quinone, aromatic rings, methyl groups, ethyl groups, aliphatic chains, is also one of the key importance of CB for rubber reinforcement (Gao et al., 2019). Nevertheless, the surface functional group types and their existence depend on the CB grade, more specifically the processing temperature and holding time. Those functional groups create rubber-CB interactions thus enhancing reinforcement in rubber products. Moreover, these surface functional groups determine the surface pH of CB which affects on curing process of the rubber compounds as well as on rubber-CB and CB-CB interactions (Greenough et al., 2021). This CB-CB interaction is reduced by lowering the oxygen-containing functional groups in CB thus the tendency to reduce filler aggregate formation while effectively dispersed during compounding. Therefore, with such importance of balancing surface functional groups in a filler, the BCh structure and the surface functional groups are essential to review when developing BCh as a suit for CB.

The main factors that influence surface functional groups of biochar are the type of feedstock and pyrolysis conditions, i.e., temperature and time (Yaashikaa et al., 2020). The surface functional groups of different BCh are characterized using Fourier Transform Infrared Spectroscopy (FTIR) and can be found in a series of literature. BCh of sugarcane bagasse shows aliphatic -CH_2, -C=O, and CH=CH, C-O groups while some of those peaks were reduced and vanished when the pyrolysis temperature was increased from 300 ^{0}C to 700 ^{0}C due to the mass losses at higher temperatures (Sun et al., 2018). Also, the analysis suggests of reduction of acidic functional groups thus turning sugarcane bagasse BCh into alkali BCh with increased pyrolyzing temperature (Sun et al., 2018). Moreover, Janu et al. 2021 studied the FTIR of twelve different BCh obtained at 300 ^{0}C, which exhibit distinctive variations of peaks corresponding to different functional groups (Janu et al., 2021). There, the functional groups that appeared in conifer wood chips BCh were diminished when the pyrolysis temperature was increased up to 750 ^{0}C (Janu et al., 2021). Similar behavior was reported by Mayakaduwa et al. in 2016 for tea waste biochar (Mayakaduwa et al., 2016). The above facts suggest that the waste BChs are composed of similar functional groups that appear in CB and the quantities of such functional groups can be lowered by increasing pyrolysis temperature to acquire more favorable surface conditions to be comparable with CB. This was exactly explained by Peterson in 2020 that the BCh produced by poplar and paulownia BCh are nearly pure carbon elements with no strong residual functional groups appearing plus no crystalline impurities which were confirmed by the FTIR and XRD patterns as given in Figure 1. And thus, it says those BChs are close to CB (Peterson, 2020).

Moreover, dead leaf BCh prepared from Tecoma dead leaf was tested against a range of pyrolyzing temperatures, and the BCh structure variation was studied by Lay et al. in 2020 (Lay et al., 2020). An important finding was revealed using Raman spectroscopic analysis using a single crystalline graphite peak at 1500 – 1600 cm^{-1} region (G-band) and a polycrystalline peak at 1300 – 1400 cm^{-1} (D-band/ disorder band). There, the D-band was shifted to lower frequencies while the intensity ratio of the two bands (I_D/I_G) was increased from 1.07 to 1.13 when the pyrolyzing temperature was increased from 550 ^{0}C to 900 ^{0}C. This indicates that the carbon structure was more and more disordered means more amorphous regions in BChs. When further increased of temperature to 1000 ^{0}C, the BCh structure removed the disorder (I_D/I_G = 0.92) showing a more crystalline structure which is similar to CB (I_D/I_G = 0.98). Here, it was again proved that the optimization of pyrolyzing conditions makes a more usable form of BCh. Therefore, BChs that are close to CB in properties and structure are possible to derive using waste biomass materials by optimized pyrolysis conditions, modifications, or treatments.

3. Study of mechanical properties of rubber compounds replaced by BCh as filler

In literature, it is found that CB was replaced with BCh from different biomass sources in rubber compounding. There, those compounds show considerable mechanical properties of their rubber compounds. Some studied 100 % replacement while some studied the partial replacement of CB in rubber compounding. When closely studying the mechanical properties of those vulcanizates, interesting findings were observed.

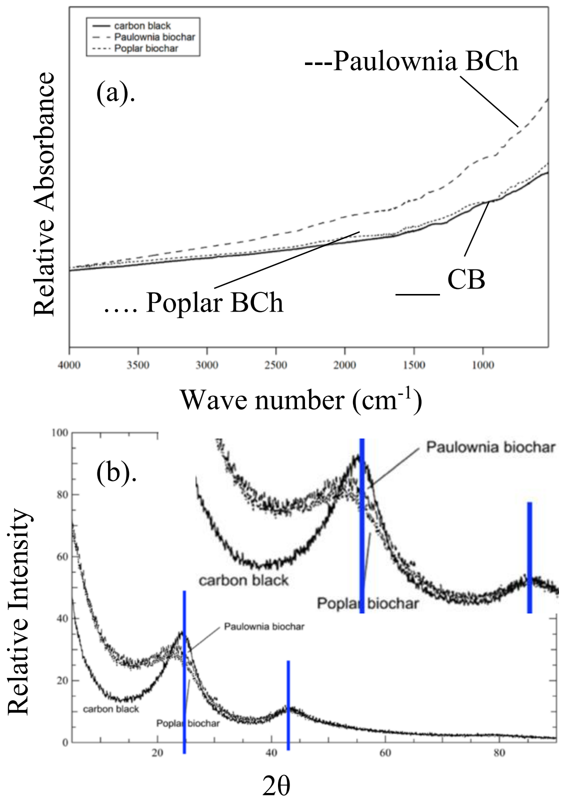

Figure 1: (a) FTIR spectrum and (b) XRD patterns of poplar and paulownia BChs and CB. Figures extracted from the original work by Peterson in 2020 (Peterson, 2020).

Iresha et al. in 2016 reported tea waste BCh used as 100 % filler for natural rubber in varied filler loadings and compared its properties with CB-filled natural rubber in the same filler loadings. There, tea waste BCh with particle size < 125 µm shows higher tensile strength, elongation at break, tear strength and rebound resilience than CB at each filler loading from 10 phr to 60 phr. The hardness of vulcanizates was lesser for BCh-filled than CB-filled samples. Authors suggested that BCh particles might have high polarity and surface irregularities in addition to the smaller particle size which caused reinforcement of natural rubber vulcanizates (Iresha et al., 2016). Further, Dead leaf biomass-derived BCh was replaced as a filler for natural rubber instead of CB. There, the tensile strength, elongation at break, and hardness properties of BCh-filled samples were given considerable values compared to CB-filled vulcanizates at 5, 10, and 15 phr filler loadings studied (Lay et al., 2020). Such full replacement of CB with BCh from different biomass sources with comparable mechanical properties concludes the BCh applicability as a rubber filler for sustainable rubber product manufacturing.

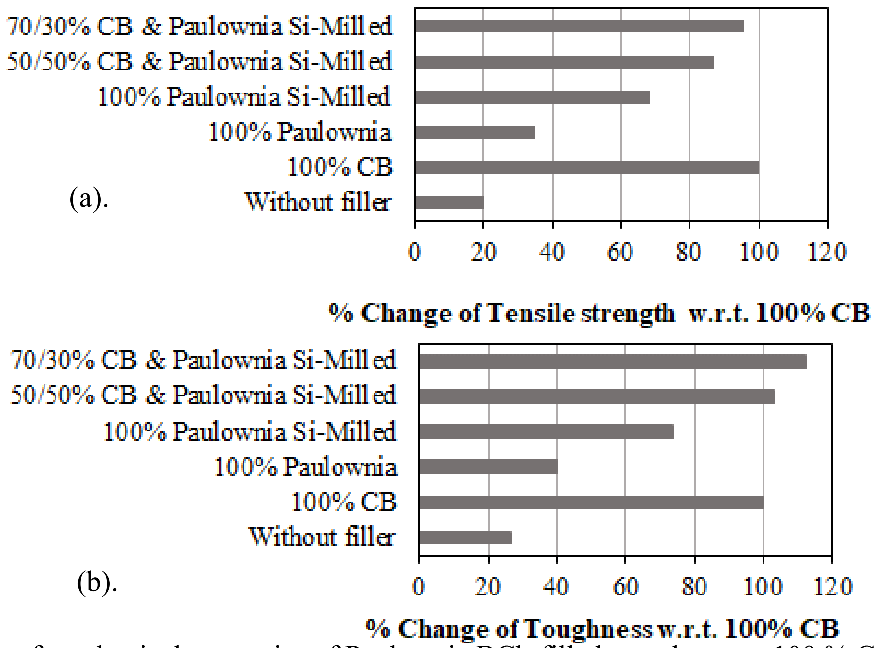

Figure 2: % Change of mechanical properties of Paulownia BCh-filled samples w.r.t 100 % CB-filled rubber vulcanizates (a) tensile strength and (b) toughness. Graphs were generated based on the literature (Peterson, 2020).

Figure 2 shows an example of the mechanical properties of vulcanizates prepared using paulownia BCh replaced with CB fully and partially. There, paulownia BCh was co-milled with 1 wt% silica (Si-milled) to reduce the BCh particle size, which this technique can be considered as a treatment to the BCh carried out to enhance the suitability of BCh to be comparable with CB (Peterson, 2020). Comparing the results, even though the 100 % BCh replacement with no Si-milled treatment did not bear good mechanical properties compared with 100 % CB-used rubber compounds, the Si-milled BCh showed almost doubled tensile strength as well as considerably enhanced elongation and toughness as per the original work (Peterson, 2020). Moreover, the BCh partial replacement to CB in different ratios exhibits almost similar or superior mechanical properties of their vulcanizates. This result is significant to consider because, in a study to embed sustainable practices while reducing the environmental impact of both raw material utilization and final product, even a partial replacement of such sustainable material makes a big impact.

4. Conclusion

The review was aimed at discussing the possibility of producing BCh and using it as filler for rubber compounding. There, it was well identified that there are abundant waste biomass sources such as rice husk, sugar cane bagasse, tea wastes, coconut shells, etc. in Sri Lanka which can be utilized for BCh production using the pyrolyze method. This BCh production is considered a zero-carbon process thus no harm to the environment will be caused. Here, BCh from waste biomass was compared w.r.t. CB because of its well-defined uses as filler for the rubber industry. The analyzed data from literature suggested > 75 % of carbon content in BCh derived from waste biomasses and most of them showed < 5 % of ash content even at lower temperature pyrolysis ~ 300 ^{0}C. However, carbon content can be improved when the pyrolysis temperature is increased to higher values around 700 ^{0}C. Here, the higher carbon, lower ash, and high surface area of BCh are more favorable factors to use as filler. Moreover, the surface functional groups and the structure of BCh can also be modified as similar to the CB surface using optimized pyrolyzing and modifications. Further, the mechanical properties of rubber compounds replaced by some BCh fully and partially showed comparable and sometimes superior mechanical properties to CB-loaded vulcanizates which support the applicability of BCh as a sustainable filler for the rubber industry. This might not be a single piece of work to develop commercial-grade BCh for rubber applications at once. Yet there is a huge potential in Sri Lanka with the abundance of waste biomass sources, the possibility of production, and optimization for commercial applications as a sustainable advanced material. Therefore, comprehensive, and interdisciplinary research must be carried out to make this valuable material a future filler material in the rubber industry with achieved sustainable goals.

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LONG SHORT-TERM MEMORY (LSTM) & FEEDFORWARD ARTIFICIAL NEURAL NETWORK (ANN) FOR FLOOD PREDICTION

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Abstract: Nowadays, floods have emerged as one of the most pervasive global environmental and economic hazards, affecting numerous countries across the world, resulting in a staggering loss of both human lives and infrastructure damage. The situation is no different in Sri Lanka. Somawathi, a region in Polonnaruwa district, is often hit by floods because monsoon rains cause the river Mahaweli to overflow. Hence, it is essential to implement a flood forecasting system to mitigate economic losses and minimize the risk to human lives. Physical-based flood forecasting methods have demonstrated limitations and inefficiencies in their effectiveness because they tend to require a large amount of input features. This study aimed to forecast the river Mahaweli flow at Manampitiya Station, which is close to Somawathi, for one day ahead using Machine Learning as the modeling tool and observed rainfall data at three rain gauges and early dis-charges at the target station as inputs. Feedforward Artificial Neural Network (ANN) and Long Short-Term Memory (LSTM) were the used model architectures. Root Mean Squared Error (RMSE) and Nash Sutcliffe Efficiency (NSE) were used for evaluation. Better results were obtained from the LSTM model compared to the ANN model for the same hyperparameters, indicating its superior performance in flow forecasting.

Keywords: flood prediction; water level; long short-term memory; artificial neural network; Mahaweli river; Manampitiya

1. Introduction

Flooding, which can be described as one of the direct outcomes of the rainfall-runoff process, leads to significant economic and social damages and casualties. It presents a potential risk to highly populated areas situated near major rivers, both upstream and downstream. Floods have accounted for approximately 30% of the total number of natural disasters over the period spanning from 1900 to 2006 claiming more than 19% of the total fatalities (Jain et al., 2018). It is anticipated that these losses will rise in the future because of factors such as climate change, increasing sea levels, land use changes, deforestation, and growth of population in flood-prone regions. Consequently, the number of people at risk of flood disasters globally is expected to surge to two billion by the year 2050 (Vogel et al., 2011).

Accurate flood flow prediction plays a crucial role in minimizing flood hazards and effectively managing water resource systems. Although achieving full protection from flood events is not always seen as a viable option due to the uncertainties regarding the magnitude, timing, place of occurrence, and geophysical interactions of floods (Moore et al., 2005), accurate forecasting will allow people in flood-prone areas to leave quickly avoiding fatalities. Nevertheless, accurately predicting river flow is a difficult task due to the intricate and dynamic nature of river flood stage analysis, involving spatial and temporal variations. Moreover, the river flow process is a nonlinear one that is affected by multiple factors. Some of them are the watershed characteristics, precipitation patterns, riverbed topography, and climatic features (Le et al., 2019). Numerous predictive techniques have been suggested to alleviate or preemptively address the consequences of floods, relying on extensive datasets for accurate forecasts.

At present, two approaches are utilized for flow prediction. The initial approach involves employing mathematical models which are also known as physical models that simulate the hydrodynamic behavior of water movement. This method is commonly employed due to its foundation in hydraulic and hydrological concepts. However, these models often necessitate a substantial amount of input data which may not always be readily accessible or easy to acquire, such as precipitation predictions and topography information.

Furthermore, the model parameters must be carefully tested and evaluated, because they are regionally dependent and can be challenging to estimate or calibrate effectively. Consequently, the models exhibit poor performance, particularly in areas with limited data availability. Additionally, conventional hydrological models have limitations in terms of flood warnings, as their runtime tends to be lengthy (Thirumalaiah & Deo, 2000). Another drawback is their inability to predict downstream flow increases resulting from sudden fluctuations in upstream flow caused by the release of water from extensive dams and reservoirs.

The second method employed for river flow prediction involves data-driven approaches that rely on the statistical correlation between output and input data. Artificial Neural Network (ANN) can be identified as one commonly used data-driven model. The data-driven approach, utilizing ANNs, shows promise as an alternative method for hydrological streamflow forecasting (Kişi, 2011). These models can be effectively implemented solely based on available rainfall data and measured discharge data, without the need for detailed catchment characteristics due to black box nature. Researchers have explored different techniques using neural network models, either independently or in conjunction with process-based models, to enhance forecasting accuracy by minimizing errors.

To address the vanishing and exploding gradient problems of ANN, it incorporates LSTM (Long Short-Term Memory) layers within its architecture. Unlike traditional Recurrent Neural Networks (RNNs), LSTMs excel at processing and forecasting time series sequences without disregarding essential information. This feature makes them highly suitable for time series forecasting tasks and is considered a standard procedure when constructing applications of this nature.

It is always valuable to investigate different methods and algorithms in hydrology due to the unique advantages they offer and their distinct approaches to modeling complex phenomena. Research and investigations in hydrology, especially in areas such as rainfall-runoff modeling, are still in their early stages. Therefore, it is imperative to conduct comprehensive computational analyses to yield more robust and insightful outcomes. This research aims to check the suitability of LSTM architecture compared to ANN inflow forecasting, using a case study in Polonnaruwa, Sri Lanka.

2. Literature Review

2.1. Artificial Neural Network (ANN)

The feed-forward artificial neural network (ANN) is composed of interconnected neurons linked by weights. Its purpose is to map a set of input data to desired output values. The structure of the ANN is depicted in Figure 1, featuring an input layer, a hidden layer, and an output layer. The input layer receives external data, which is subsequently passed through the hidden layers until it reaches the output layer. This process is commonly referred to as a forward pass (Ghassemlooy et al., 2010).

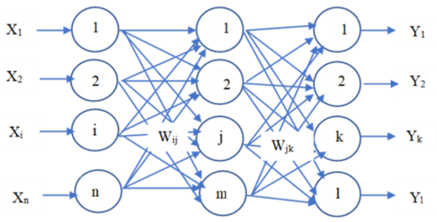

Figure 1: ANN Architecture.

Each layer contains multiple neurons, and the connections between different layers are established using weights and biases. For any layer, activation from the previous layer is taken, multiplied by the weight matrix of the current layer, and bias is added. Then, this linear transformation is fed to a nonlinear activation function before passing into the next layer.

2.2. Long Short-Term Memory (LSTM) Algorithm

The Long Short-Term Memory (LSTM) architecture is a specialized type of recurrent neural network (RNN) designed to address the limitation of traditional RNNs in capturing long-term dependencies (Figure 2). Unlike RNNs, LSTM incorporates an additional cell state or cell memory (c_t) where information can be stored, along with gates (represented by dashed rectangles in Figure 2) that regulate the flow of information within the LSTM cell.

The first gate, known as the forget gate, denoted by a red rectangle, determines the extent to which elements of the cell state vector (c_{t-1}) will be forgotten. The second gate, denoted by a green rectangle, known as the input gate or compute gate, updates the cell state in the current time step. The third and final gate, shown by a blue rectangle, known as the output gate, manages the information from the cell state (c_t) which moves into the new hidden state (h_t). For all the gates, the current input (tx) and the previous hidden state (h_{t-1}) are used with gate-specific weight and bias terms. Particularly, the cell state (c_t) is responsible for learning long-term dependencies effectively. It can retain information unchanged over an extended number of time steps due to its simple linear interactions with the rest of the LSTM cell.

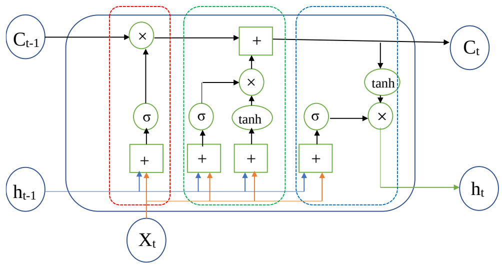

Figure 2: LSTM Architecture.

2.3. Root Mean Square Error (RMSE)

The root mean square error (RMSE) is a widely adopted statistical metric for assessing model performance in various fields such as meteorology, air quality, and climate research. It serves as a standard measure to evaluate the accuracy and reliability of models in these domains. Equation 1 denotes the RMSE calculation for the data set.

$$RMSE = \frac{1}{n}\sum_{i=1}^{n}(y_i - y_i')^2 \qquad (1)$$

Where n is the amount of data in the sample, y_i and y_i' are the actual and predicted outputs for the i^{th} input.

2.4. Nash–Sutcliffe model efficiency coefficient (NSE)

In the field of hydrologic modelling, calibration of the models is typically necessary before their application. Traditionally, the correlation coefficient and standard error of estimate have been employed as metrics to assess the quality of the model calibration. However, it should be noted that the correlation coefficient is primarily suitable for linear models with an intercept.
Recognizing the limitations of the correlation coefficient, Nash, and Sutcliffe in 1971 introduced an alternative index to evaluate the goodness of fit, known as the efficiency index (E_f). Equation 2 exhibits the E_f calculation.

$$E_f = 1 - \frac{\sum_{i=1}^{n}(y'_i - y_i)^2}{\sum_{i=1}^{n}(y_i - y'')^2} \qquad (2)$$

Where y'_i and y_i are the predicted and the actual results while y'' is the mean of the predicted results. N is the sample size. When examining the predictions of a linear model, an efficiency index falling within the range of 0 to +1 indicates unbiased predictions. A value close to 1 indicates that the model a has good predictive skill.

2.5.Multivariate Imputation by Chained Equations (MICE)

Missing data is a common problem in every analytical research. In statistical literature, Multivariate Imputation by Chained Equations (MICE) is described as a righteous method for filling missing data. MICE is praised in statistical literature for its effectiveness in filling in missing data. It generates multiple imputations, accounting for statistical uncertainty and improving accuracy. MICE is also flexible and can handle different data types. However, it requires that the missing data be Missing At Random (MAR), meaning their likelihood of being missing depends solely on observed values. The MICE procedure involves six steps. 1- Basic imputation, often using the mean, for all missing values. 2- Resetting mean imputations to missing for one variable. 3- Regressing the variable from Step 2 using other variables in the model. 4- Replacing missing values with predictions from regression models. 5- Repeating Steps 2-4 for all variables with missing data in one cycle. 6- Repeating Steps 2-4 for multiple cycles until all missing values are replaced with predictions reflecting observed data relationships (Van Buuren & Groothuis-Oudshoorn, 2011)..
Overall, MICE is a robust method for dealing with missing data in analytical research.

3. Methodology

3.1. Study Area and Data

Sri Lanka has 103 rivers, and the total length of the rivers is around 4500 km. Mahaweli River, which is the longest river in Sri Lanka, is 335 km long. It originates in the central hills of Sri Lanka, beginning its journey as a collection of several small creeks. One of these initial creeks is the Agra Oya, sourced from Horton Plains. The river flows through the central region of Sri Lanka, eventually reaching its terminus at the southwestern side of Trincomalee Bay, where it meets the Bay of Bengal. Mahaweli River Basin (MRB) is the largest river basin in Sri Lanka, encompassing an approximate area of 10,448 km^2, which accounts for approximately 16% of the country's total land area (Diyabalanage et al., 2016). Approximately 40% of the country's total electricity demand is met through hydropower generated by the river. Simultaneously, the Mahaweli River provides a substantial water resource essential for the cultivation of crops such as rice and vegetables (Withanachchi et al., 2014). The runoff of Mahaweli contributes to one-seventh of the total runoff of all the rivers in Sri Lanka, having a mean annual runoff of 8.8×10^9 m^3 (De, 1997).

The distribution of rainfall is uneven in spatial and temporal due to the topographical features of the basin. MRB can be divided into two main parts considering the topography, which are 'The Upper Mahaweli Basin' (UMB) and 'Lower Mahaweli Basin' (LMB) (Hewawasam, 2010). The UMB belongs to the western part of the central highlands, having a total annual precipitation of around 6000 mm (Zubair, 2003). The mean annual precipitation for the LMB varies from about 1600–1900 mm.

Sri Lanka gets the rainfall due to southwest monsoon (SWM; June–September), northeast monsoon (NEM; December–February), first inter-monsoon (FIM; March-May) and second inter-monsoon (SIM; October–November), respectively (Wickramagamage, 2016). The precipitation in UMB is mostly affected by the southwest monsoon, while the precipitation in LMB is affected by the northeast monsoon due to the complexity of the terrain and the monsoon pattern in Sri Lanka (Shelton & Lin, 2019).

The Somawathi area, which is downstream of Parakrama Samudra reservoir, Polonnaruwa district, belongs to the LMB and is susceptible to flooding. People in that area must leave to avoid floods almost every year. Usually, floods occur during December to February indicating its correlation to NEM. Manampitiya is a river gauge station, which is in the study area and is a good indicator to check the flood level. Polonnaruwa Agri., Angamedilla, and Aralaganwila are three meteorological stations, that are close to Manampitiya station and are located upstream. Therefore, rainfall in these stations along with the water level at Manampitiya, were used as the inputs. The Irrigation Department of Sri Lanka website provides the real-time water level along with the alert level, minor flood level, and major flood level for the river gauge. Therefore, prediction of water level allows people to determine the occurrence of floods in this area.

Because this study focuses on assessing the models' ability in water level forecasting and the effects of sequential data characteristics on model performances, the statistics of the data, and the correlation of the data series are considered. The LSTM model was constructed to forecast the water level at Manampitiya station with one day lead time and the ANN model was used as a benchmark model to compare the accuracy of predictions. Figure 3 shows the map of the study area.

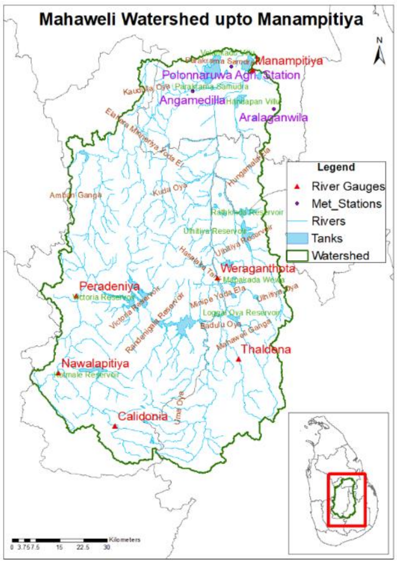

Figure 3: Map of the study area.

The following Table 1 shows the data set summary while Table 2 denotes the Pearson correlation coefficients among the rain gauges and the river gauge. The coefficient is higher when the current day rainfalls and the water level on the following day are considered (Corr_t+1) rather than considering the same day values (Corr_t). According to the table, when the lag time between rainfall and water level increases, the coefficient value decreases (Corr_t+2, Corr_t+3, and Corr_t+4). This gives an idea about the rainfall-runoff process near the outlet.

Table 1: Data set summary

Water Level (m) and Rainfall (mm)				
	Station Name			
	Aralaganwila	Angamedilla	Polonnaruwa Agri	Manampitiya
count	10319	10319	10319	10319
mean	4.94584	4.820227	4.20901	33.382384
std	15.083687	15.451919	13.486747	0.643105
min	0	0	0	32.196
max	225.8	222	184	37.254333

Table 2: Pearson correlation coefficients among the rain & the river gauges

Rain gauges	**Corr_t**	**Corr_t+1**	**Corr_t+2**	**Corr_t+3**	**Corr_t+4**
Angamedilla	0.2267	0.3441	0.3429	0.3118	0.2886
Aralaganwila	0.2824	0.3607	0.3531	0.3248	0.2968
Polonnaruwa Agri	0.2382	0.3335	0.3341	0.3115	0.28

Therefore, it can be concluded that there is a higher effect on the water level from rainfall on previous days rather than on the current day.

The data gathered within the study area consisted of daily measurements of water level and precipitation. Precipitation data were recorded in millimeters (mm), while water level measurements were taken in meters (m). Data for 28 years, from 1984 to 2012 were taken into consideration. The missing value percentages of Aralaganwila, Angamedilla, Polonnaruwa Agri, and Manampitiya were 0.029%, 0.899%, 2.128%, and 3.553% respectively. Missing values were filled by the following methods.

i. For the water level, the missing value for a particular day was taken as the mean of the values for the same day in all the other years. This method was considered to be suitable because of the seasonal pattern and the smooth trend of the water level. (eg: - the value for 1984-05-01 is the mean of the values on May 1st in the other years.)

ii. For the precipitation data, the missing values were filled using the MICE method.

Figure 4 shows the water levels after imputation. Peaks of the water level can be observed from November to March, every year.

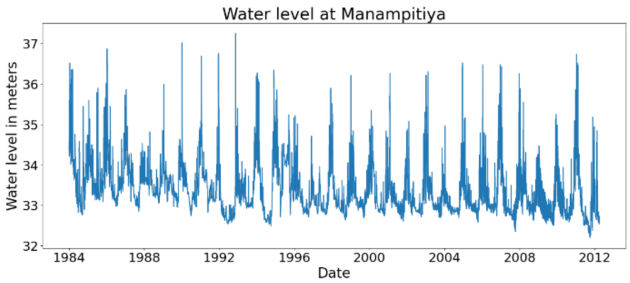

Figure 4: Water level at Manampitiya.

3.2. Data normalization

After data imputation, data normalization was done. This step entailed rescaling the data to a range between -1 and 1, using Standard Scaler. It considers the mean and the standard deviation in each feature column. Equation 3 was used to normalize the data.

$$z = \frac{x-\mu}{\sigma} \quad (3)$$

where x is the input data, σ and μ are the standard deviation and the mean of the data.
Following normalization, the data were split into two sets, the training set, and the test set. The training set encompassed 70% of the data, providing a substantial amount for model training and parameter estimation. The remaining 30% of the data was allocated to the test set, serving as an independent dataset to assess the model's predictive capabilities. With the model trained using the training dataset, predictions were made based on the test set.

3.3. Model Settings and Parameterization

The subsequent step involved constructing and fine-tuning LSTM and ANN networks designed for predicting the water level at Manampitiya Station with a one-day lead time. Tuning involved assessing two key parameters: the moving window size and the model architecture.

3.3.1. Moving window size

The LSTM model consisted of an input layer, a hidden layer comprising 64 cells, and an output layer that produced a single-value prediction. The validation split was 0.1 of the train set while the learning rate and the batch size were set to 0.001 and 32 respectively. The optimizer was ‘Adam’ and ‘Mean Squared Error’ was the loss function. ‘ReLU’ was the activation function for the hidden layer. The

'Early Stopping' criterion was used to avoid overfitting. Before evaluating the models, all the water level values were converted into centimeters.

A moving window with a size of n means, the model takes past n number of observations to predict the next observation and so on. The autocorrelation plot of the Manampitiya River gauge data (Figure 5) was generated and it could be seen that the number of days corresponding to the correlation value of 0.5 was around 10,20 or 30. Then the n was changed to 5 to 30 with a step size of 5. 15 was selected as suitable with the minimum RMSE value of 27.87 and the maximum NSE value of 0.797. That means the models use 15 days of water level and precipitation data to predict the water level on the 16th day.

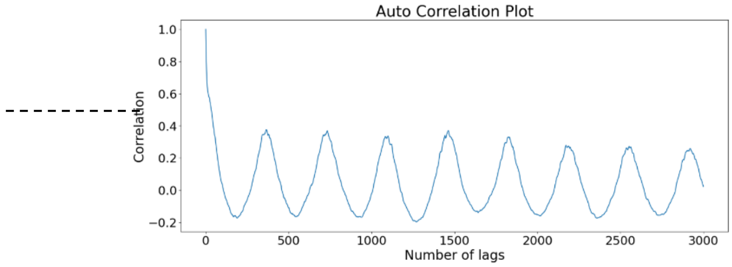

Figure 5: The autocorrelation plot of the Manampitiya water level.

3.3.2. The model architecture

After choosing the moving window size, the model was tuned for different architectures while keeping all the parameters the same. Three hidden layer models with 32 cells, 64 cells, and 128 cells, 2 two hidden layer models with 128+32 cells, 128+64 cells, and one three hidden layer model with 128+64 cells+16 dense neurons were the checked architectures. All the RMSE values ranged between 27.83-27.96 and NSE between 0.797 – 0.795. One hidden layer with 64 64-cell model was chosen with an RMSE value of 27.83 and an NSE value of 0.797.

4. Results

After creating the LSTM model, the ANN model was created. Replacing the hidden LSTM layer with a dense layer with the same number of units, which is 64, was the only change. Both models were constructed by using four inputs which are precipitation from three stations and water level in the target station for the previous 15 days which resulted as follows, shown in Figure 6, Figure 7, and Figure 8. The ANN algorithm yielded an RMSE error of 29.74 and an NSE value of 0.768. The comparison of the RMSE and NSE values of the two models is shown in Figure 9.

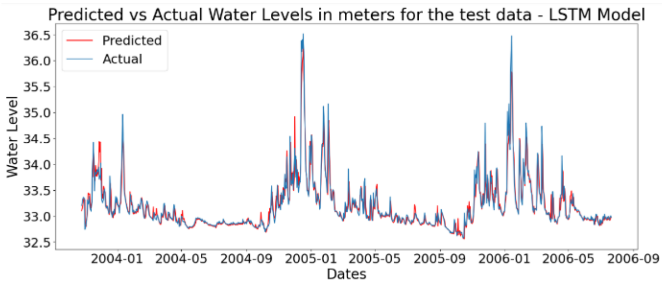

Figure 6: Predicted and actual results for the first three years of the test data – LSTM model.

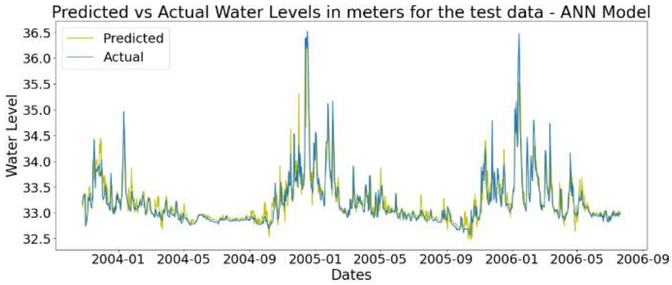

Figure 7: Predicted and actual results for the first three years of the test data – ANN model.

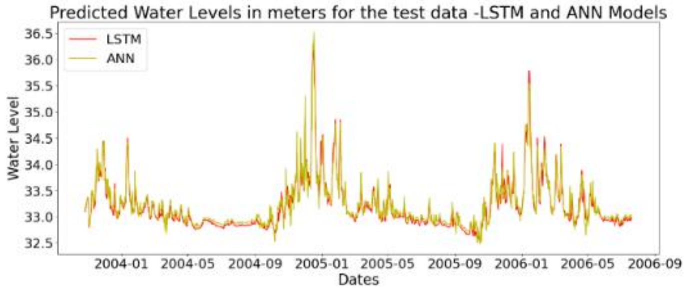

Figure 8: Comparison of the predicted results of the two models for the first three years of the test data.

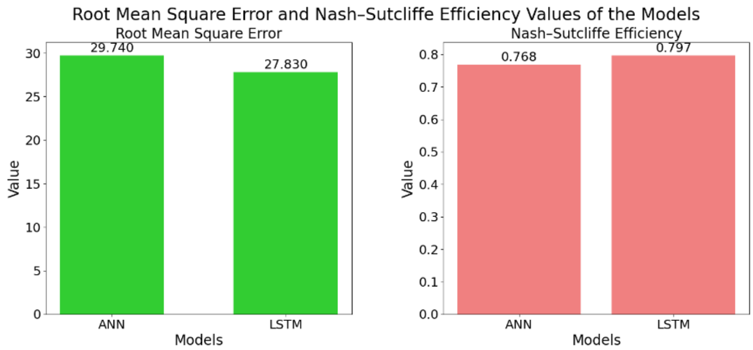

Figure 9: Comparison of the RMSE and NSE values of the two models.

5. Discussion and conclusion

The prediction of the water level at Manampitiya station using the LSTM algorithm yielded the lowest RMSE error of 27.83 and NSE value of 0.797 while the ANN algorithm yielded a RMSE error of 29.74 and NSE value of 0.768, which means the error generated when predicting the water level at the target station is 29.74 cm compared with the actual water level. According to Figure 6, Figure 7, and Figure 8, there is a higher deviation between the predicted and the actual results for the ANN model compared to the LSTM model. The line that corresponds to the predicted water level in the ANN model goes above the actual water level line on many occasions. That means the ANN model overestimates the water level in many instances. Further, on some occasions, the ANN model underestimates the downward peaks in the water level.

When considering the LSTM model, the line that corresponds to the predicted water level is close to the actual water level line which indicates the higher accuracy of the model. Although the LSTM model over-predicts some upward peaks of the water level, it is not very significant compared to the ANN model. Further, results do not show sudden underestimations of downward peaks in the water level such as in the ANN model. According to Figure 10, the prediction line in the ANN model is always above the line in the LSTM model, which indicates a higher deviation between actual and predicted values, resulting in a higher error in the ANN model.

According to the results, Long Short-Term Memory conducted more accurate prediction in flood disasters when compared to Artificial Neural Networks because it yields a lower RMSE value and a higher NSE value.

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REVIEW OF NATURE-INSPIRED SOLUTIONS FOR DISASTER RISK REDUCTION

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Abstract: This research advocates for a transformative shift in the built environment towards disaster risk reduction (DRR) and promoting design, operational, and systematic approaches in using Nature Inspired Solutions (NIS) to achieve DRR. The article primarily focuses on ecological and social systems with the shift from conventional sustainability and resilience strategies within the practice. Exploration of novel technologies and biomimicry is required to accomplish this, exposing untapped potential in NIS for DRR. Despite expanding biomimicry research, this study underscores the lack of biomimicry research in DRR and indicates prospects for 'system-level' applications. The comprehensive literature review discloses gaps in the articulation of sustainability and resilience, advantages, and recommends convergence with broader industry trends. The research submits a comprehensive analysis as well as the foundation for constructing innovative solutions in the area of NIS for DRR. It facilitates a thorough understanding for scientists, policymakers, planners, and other stakeholders in the area of NIS for DRR as a documented literature source. The paper aims to promote a more structured and organized understanding of the current state of the art in NIS for DRR, whereby deriving objectives as such; identifying current approaches suggested by other researchers and the ones that are already implemented, discussing the current limitations associated with applying biomimicry for DRR and any suggestions of improvement, take a look at the prospects in this study area and impart any ideas for future reference and mainly to emphasize on the importance of NIS in DRR in the current stage of globalization aiding the betterment of tomorrow.

Keywords: Nature Inspired Solutions (NIS); Disaster Risk reduction (DRR); Biomimicry; Green Infrastructure; Eco – system

1. Introduction

1.1 What are Nature-Inspired Solutions?

Nature has played a pivotal role in the process of understanding sustainability in the past few decades. It has always been the foundation concept in our attempt to address

pressing environmental and social issues in all research areas. The concept of Nature-based solutions (NbS) came into light about two decades ago. According to the World Wildlife Foundation (WWF) (2023), it refers to a set of activities or policies that harness nature's power to address some of our most serious societal concerns, such as risks to water security, increased catastrophe risk, or climate change. These solutions include maintaining biodiversity and promoting human well-being by protecting, restoring, and managing ecosystems in ways that strengthen their resilience and ability to meet societal concerns. Verifying the idea presented by WWF, Forbes (Jeff Opperman, 2022) based on an article dating a year back with the same interpretation for NbS. They also highlighted how the concept created a great deal of debate and discussion among researchers on applying this concept in action. The standard definition of NbS was in- produced by the International Union for Conservation of Nature (IUCN), “Actions to protect, sustainably manage, and restore natural or modified ecosystems, that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits.” Nowadays due to the increased number of researchers on the concept the same idea of NbS is conveyed in different words for the readers to get a grip on. Coming back to the previously highlighted point in the debate amongst researchers addressed by Forbes, they highlight that some have mentioned this concept to be too vague and greenwashing.

However, drawing out the general definition of NbS gives rise to a three-pillar intervention, addressing one or more societal challenges, followed by the use of ecosystems to address the problem, and finally delivering parallel outcomes in the betterment of people as well as biodiversity. To highlight the idea if I may use an example, The Man- grove forests – First and foremost it addresses pressing issues such as erosion, sustain- ing fisheries, and strong storms. The second pillar is using ecosystems, and it is verified by the fact that mangrove forests are indeed identified as Ecosystems themselves because they provide a self-sustaining environment for both flora and fauna according to research put forth by The University of Wisconsin (Bandon. M. Wolf, 2012). Fi- Finally, if the outcomes are discussed, Mangroves operate as natural buffers, absorbing the impact of heavy waves, particularly during tropical storms, and counteracting damage produced by wave action over time, they also absorb sediment runoff from both natural and human activity, earning them the moniker "carbon sinks." Mangrove roots provide critical habitat for young fish, including species such as snapper and grouper, by providing shelter with less competition and predation. They also act as an important nursery habitat for young fish species, supporting both estuary and reef fishes.

The NbS concept underlines several values and benefits surpassing the example I’ve previously put forth. It safeguards biodiversity, restores efficiency, increases food security, Disaster Risk reduction, helps in the efforts of obtaining clean water, provides health and well-being, purification of air, and creates footsteps towards climate control (Nature Based Solutions, 2023). The same organization also presented what falls under the general umbrella of Ecosystem functions and services. The list included Carbon storage, waste decomposition, coastal protection, aesthetics, disease control, and climate regulation as some of the key functions of using NbS.

1.2 What is Disaster Risk Reduction?

A disaster is defined as an unexpected event that occurs within a specific timeframe and has a negative impact on life, property, livelihoods, and the environment to the point where external assistance is required to manage the calamity and its aftermath, restoring the environment to its normal state (Disaster, 2023). These occurrences might occur suddenly, as in earthquakes, or gradually over time, like in a drought season. Natural disasters, man-made disasters, and hybrid disasters are the three types of catastrophes. Natural catastrophes, in general, are those caused by natural processes or that have no direct human involvement. They cause substantial loss of life and property and are classified into geophysical, hydrological, climatological, meteorological, and biological subcategories (Rajesh Rajput, 2022). Disaster risk reduction (DRR) is the concerted effort to mitigate existing disaster risks, and residual risks, and contributes to strengthening resilience towards achieving sustainable development. Understanding catastrophic risk entails comprehending the intricate interaction of risks, vulnerabilities, and exposure. Natural and man-made hazards, such as earthquakes, floods, and wildfires, pose potential risks. Vulnerabilities are the variables that make individuals and groups vulnerable to the impacts of these hazards, whereas exposure refers to the danger's proximity and degree of interaction. DRR approaches these difficulties in a comprehensive and integrated manner.

Climate change, disaster preparedness, and urban pressures, according to UNESCO (2023), are converting natural risks into tragedies, resulting in both human and economic losses. The UNESCO disaster risk reduction agenda is a critical problem for UN countries. The Sendai Framework, supported by UN countries since 2015, outlines the worldwide policy for disaster risk reduction, with a goal date of 2030. The United Nations places a priority on "the substantial reduction of disaster risk and losses in lives, livelihoods, health, and in the economic, physical, social, cultural, and environmental assets." Science, technology, resilience innovation, early warning systems, the built environment, school safety, and ecosystem-based post-disaster response systems are all part of UNESCO's commitment to disaster risk reduction. Disaster management entails planning, preparation, prevention, relief, reaction, and evaluation.

The significance of disaster risk reduction cannot be emphasized, especially in light of the world's rising environmental concerns and population. Disasters have far-reaching consequences that go beyond mortality and infrastructure damage, affecting businesses, displacing citizens, and deepening socioeconomic disparities. By investing in disaster risk reduction, societies can break the cycle of disaster-response recovery and transition to a more sustainable and resilient future. One of the key benefits of DRR is its ability to save lives. Early warning systems, community preparedness programs, and good risk communication all help to decrease the number of catastrophe casualties. Furthermore, by addressing the core causes of vulnerability, DRR helps community well-being and safety, promoting a resilient culture.

1.3 Concept of Applying Nature-Inspired Solutions for Disaster Risk Reduction

Nature-based solutions (NBS) utilize the inherent resilience of natural ecosystems to provide a holistic and sustainable approach to disaster risk reduction. These solutions include a variety of techniques emphasizing environmental services, biodiversity protection, and active community participation. Principles like ecosystem-based adaptation, increasing ecological connection, and incorporating traditional knowledge are at the heart of NBS (Opperman, 2023)

Ecosystem-Based Adaptation (EbA) is a guiding idea for Nature-Based Solutions. It entails utilizing biodiversity and ecosystem services to assist communities in adapting to climate change and reducing disaster susceptibility. EbA recognizes the usefulness of natural processes in delivering important services such as flood management, water purification, and soil stabilization rather than depending primarily on traditional infrastructure (Udo, 2023) The preservation and restoration of ecosystems, as promoted by NBS, adds to community resilience. Another important NBS principle is the fostering of ecological connectedness. NBS emphasizes the necessity of protecting and repairing natural habitats by seeing ecosystems as linked networks. This connection improves ecosystems' capacity to absorb and ameliorate the effects of catastrophes, allowing species mobility and promoting biodiversity. NBS recognizes that healthy ecosystems are critical for community resilience and well-being (Dimensions, 2020)

Nature-based solutions cannot succeed without the support of the community. There is a better chance of success and sustainability if local communities are involved in the design, implementation, and administration of NBS. Local knowledge and traditional traditions are important in selecting and implementing NBS, generating a sense of ownership and responsibility (Rajput, 2022). This community-based approach guarantees that disaster risk reduction initiatives are both effective and culturally respectful. Na- ture-Based Solutions incorporate biodiversity protection, recognizing the interconnection- activity of healthy ecosystems and the broad array of species they sustain. Conserving biodiversity via NBS protects natural systems' integrity and improves their ability to offer critical services to communities. Biodiversity helps ecosystem resilience by allowing them to survive and recover from disruptions, especially those induced by natural catastrophes (WWF, 2020)

Natural defenses, such as mangroves, coral reefs, and dunes, are frequently restored as part of Nature-Based Solutions. These habitats serve as natural barriers to storm surges, coastal erosion, and floods. Mangrove forest restoration, for example, may greatly minimize the impact of tsunamis and storms on coastal areas. NBS recognizes the effectiveness of these natural defenses and works to restore and preserve them to improve disaster resilience. Nature-based solutions are built on a multi-benefit approach. This approach recognizes that natural interventions might give benefits other than disaster risk reduction. Among the many advantages of NBS are improved water quality, improved recreational places, carbon sequestration, and higher aesthetic value. This coincides with the wider aims of sustainable development, which address various difficulties at the same time (UNESCO, 2023).

Integrating Nature-Based Solutions into larger disaster risk reduction initiatives requires policy integration. Policymakers and planners have an important support role- ing and rewarding NBS adoption at all levels. Incorporating NBS into policy frameworks means that new techniques be examined alongside traditional methodologies in infrastructure development and land-use planning decision-making processes. Finally, Nature-Based Solutions provide a holistic and long-term strategy for managing disaster risks. NBS promotes resilience, biodiversity conservation, and sustainable development goals by utilizing ideas such as ecosystem-based adaptation, ecological connection, and community engagement. Nature-based solutions, by recognizing the interconnectedness between human societies and the natural world, provide the path for a more peaceful and resilient cohabitation.

2. Literature Review

2.1 The current scope of implementing NIS in DRR

The world as it is today has shifted its focus toward sustainability. When compared to a decade ago the entire paradigm shift has facilitated some interesting ideas of incorporating Nature Inspired or Nature-based solutions. Some of the key concepts followed through and are being implemented are as such,

- **Nature-based solutions in harnessing catastrophe**

Mitigation of Floods and Storm surges

Floodplain Restoration: This is the repair of natural floodplains, which serve as natural reservoirs during heavy rains. Water may be gradually absorbed and released by re-building floodplains, minimizing the danger of flooding downstream (Roni, 2019). This technique also contributes to the preservation of environmental balance and biodiversity. In the United States, restoration of the Upper Mississippi River floodplain has entailed restoring it to its natural flood regime, lowering the risk of downstream flooding, and safeguarding towns (UMRR, 2023).

Coastal Wetland Preservation: Coastal wetlands, such as mangroves and salt marshes, play an important role in storm surge mitigation. They operate as natural barriers, absorbing wave impact and minimizing storm surge severity. These wetlands must be preserved to safeguard coastal regions from the devastating powers of storms and surges (Runting, 2016). The preservation of mangrove forests in Bangladesh and India's Sundarbans Delta, for example, is critical for sheltering coastal towns from storm surges caused by cyclones (Sayed, 2004).

Landslide prevention and Soil stabilization

Reforestation: Planting trees on slopes helps to stabilize the soil and prevents landslides. Tree roots bind to the soil, which reduces erosion and improves slope stability. Furthermore, the capture of precipitation by the tree canopy aids in surface runoff control, reducing the danger of soil saturation and landslides (Shaun, 2015). In China, the "Green Belt" initiative comprises afforestation on slopes to reduce soil erosion and landslides, particularly in disaster-prone areas (Giacomo, 2021).

Terracing: Building terraces in steep terrain entails laying out a succession of level platforms on the slope. This method slows down water discharge, enabling it to be absorbed by the soil. Terracing also gives the soil physical stability, keeping it from rolling down the hill after heavy rain (Dorren, 2000). Terracing has been used to stabilize slopes and preserve agricultural areas from erosion in the Himalayan region, where landslides are a major concern (Sen, 2009).

Coastal protection and Erosion control

Mangrove forests: Mangroves provide a natural barrier against coastal erosion and storm surges. Their intricate root systems help to stabilize the beach, decreasing the wave effect and safeguarding coastal regions from erosion (Friess, 2019). Mangroves also provide a home for a variety of marine creatures, helping to conserve biodiversity. The Sundarbans mangrove forest in Bangladesh and India not only protects coastlines but also supports a variety of habitats and livelihoods (Friess, 2012)

Coastal vegetation: Planting and conserving vegetation near beaches, such as grasses and bushes, aids in erosion management by trapping sediments and improving the stability of coastal soils. This not only guards against erosion but also strengthens coastal ecosystems' resistance to climate-related issues (Danielson, 2005). The "Living Shorelines" approach, which emphasizes the use of ecosystems such as plants and oyster reefs, has been used in several sites, including the United States' Chesapeake Bay (Garland, 2015).

- **Nature-Based Applications in Urban Settings**

Green Infrastructure in Cities

Parks: There are numerous advantages to incorporating parks into urban planning. Parks serve as the lungs of cities, producing oxygen and absorbing carbon dioxide. They also provide recreational spaces for residents, which contribute to their physical and mental well-being. Examples include Central Park in New York City and Hyde Park in London (Friedman, 2019).

Green roofs: Green roofs involve the cultivation of vegetation on the roofs of buildings. They improve insulation, lowering the energy required to heat and cool buildings. Green roofs also absorb rainwater, lowering stormwater runoff and the risk of urban flooding. One example is the Chicago City Hall Green Roof, which has become a model for sustainable urban development (Cidell, 2017).

Permeable pavements: Water may travel through these pavements, lowering surface runoff and reducing the strain on urban drainage systems. Permeable pavements aid in stormwater management, restore groundwater, and reduce the urban heat island effect. One example is the usage of permeable pavers to alleviate stormwater runoff concerns in Portland, Oregon (Sholtz, 2007).

Urban forests and green spaces

Urban forests: By absorbing pollutants and giving oxygen, trees planted and maintained in metropolitan areas help to enhance air quality. Trees also serve as carbon sinks, aiding in the mitigation of climate change. In places such as Los Angeles and New York, the Million Trees Initiative attempts to boost urban tree canopies and improve environmental sustainability (Robert, 2015).

Green spaces: Aside from woods, building green spaces within cities, such as community gardens and tiny parks, has several advantages. These areas promote biodiversity, improve mental health, and build a feeling of community. The High Line in New York City and Singapore's Gardens by the Bay are two examples (Henderson, 2013).

Carbon sequestration: Urban trees play an important role in carbon dioxide sequestration, helping to counteract the carbon emissions associated with city living. Tree species selection, adequate care, and urban forestry programs all help to maximize carbon sequestration. Cities such as Tokyo, for example, have launched programs to enhance tree cover to trap carbon (Iwasaki, 2017)

Rooftop gardens and green roofs

Energy consumption: Green roofs and rooftop gardens provide natural insulation, minimizing the need for artificial heating and cooling. As a result, energy is saved, and greenhouse gas emissions are reduced. The California Academy of Sciences in San Francisco has a green roof that aids with temperature regulation (Henderson, 2013).

Urban heat mitigation: Rooftop gardens and green roofs absorb sunlight and release it through a process known as evapotranspiration, which cools the surrounding air. This contributes to the reduction of the urban heat island effect, in which cities suffer greater temperatures than surrounding rural regions. The Bosco Verticale (Vertical Forest) in Milan, Italy, is a well-known example of a green residential tower with considerable greenery (Tzortzi, 2019).

- **Harnessing Wetlands for Disaster Resilience**

Wetland Restoration and Preservation

Floodplain functionality: Wetlands, especially floodplains, are critical components of a natural water management system. During heavy rains, they absorb surplus water and reduce the severity of floods downstream. For example, in the United States, the restoration of wetlands along the Mississippi River has been a significant component of attempts to control and lessen the impact of floods (Price, 2020).

Biodiversity and water quality: Wetlands provide habitat for a wide variety of plant and animal species, as well as improving water quality. Wetlands conservation and restoration benefit not just biodiversity but also water quality. The Everglades in Florida, USA, is an excellent example of wetland restoration operations aimed at improving ecological resilience and water management (Lomeu, 2022).

Wetlands as natural sponges

Stormwater retention: Wetlands operate as natural sponges, absorbing surplus precipitation and limiting rapid flow. This function is critical in metropolitan environments, where impermeable surfaces enhance flooding danger. Cities such as Melbourne, Aus- Australia, have used stormwater retention systems to reduce the impact of excessive rainfall on urban infrastructure (Yan, 2022).

Groundwater recharge: Wetlands help to groundwater recharge in addition to surface water control. Wetlands recharge subsurface aquifers by slowing down and allowing water to soak into the soil (Healy, 2023). The restoration of wetlands in California's Sacramento-San Joaquin Delta aims to alleviate water scarcity concerns through creased groundwater recharge (Criss, 1996)

Mangroves in coastal resilience

Wave energy dissipation: Mangroves disperse wave energy through their extensive root systems, functioning as a natural barrier against storm surges. This serves to safeguard coastal regions from the devastating force of storm waves (Janssen, 2007). The Sundarbans between Bangladesh and India, one of the world's biggest mangrove forests, is a prominent example of mangrove coastal protection.

(Friess, 2012)

Shoreline erosion prevention: By stabilizing coastal soils, mangroves play an important role in avoiding coastline erosion. Mangrove tree roots trap sediments, strengthening the shoreline and shielding it from the erosive impacts of tides and waves (Eun, 2007). The Biscayne Bay Mangrove Coastal Wetland in Florida, United States, exemplifies the use of mangroves in coastal stabilization (Bacopoulos, 2021)

Biodiversity support: Mangroves create a unique habitat that supports a wide variety of marine species. Preserving mangrove environments not only contributes to disaster silence but also biodiversity conservation. The Great Barrier Reef in Australia benefits from mangroves along the shore, which improves the reef's overall resilience (Richards, 2018).

- **Re-forestation as a shield against Calamities**

Forest conservation

Biodiversity preservation: Forests are home to a vast array of plant and animal species contributing to global biodiversity. Conservation efforts are necessary to maintain the ecological balance they bring out ensuring the survival of various ecosystems (Naidoo, 2005). The Sinharaja Rainforest, known for its biodiversity is a prime example where forest conservation is essential for the preservation of numerous species. Sahara Desert if taken as an example was a green land centuries ago, which turned into a desert over the course of natural species loss. Avoiding such changes can help in protection against calamities such as droughts (Samarasinghe, 2022).

Water regulation: Forests are critical in managing water flow. The canopy of trees slows down rainfall, enabling it to gradually permeate the soil. This process aids in the re-charging of groundwater, the maintenance of streamflow, and the prevention of both floods and droughts. The protection of Africa's Congo Basin Forest is critical for managing the Congo River's flow and maintaining the region's water supplies (Nidhi, 2021). Wildfire risk reduction: Healthy forests provide a natural barrier against wildfires by keeping vegetation wet. Forest protection activities involve fire management methods to prevent wildfires from spreading uncontrollably. Forest conservation is critical in minimizing the danger of catastrophic fires in areas where wildfires are a big concern, such as California, USA (Hanbury, 2021).

Afforestation and reforestation projects

Stabilizing slopes: Afforestation is the practice of planting trees in regions where there have been no prior woods, whereas reforestation is the practice of replanting in deforested or degraded areas. Both activities help to stabilize slopes and avoid landslides. By planting trees along the Belt and Road Initiative routes, China's "Green Belt and Road" afforestation effort attempts to combat soil erosion and desertification (Giacomo, 2021).

Waterflow regulation: Afforestation and reforestation efforts also manage water flow, lowering the danger of floods and droughts. The Bonn Challenge, a global project to reforest and rehabilitate 350 million hectares of deforested and degraded land by 2030, shows how large-scale afforestation and reforestation may help with disaster risk reduction and sustainable land management (Temporton, 2019).

Landslide mitigation

Root systems and soil stabilization: Soil Stability and Root Systems: Forest tree root systems help bind soil particles together, reducing soil erosion and landslides (Hudek, 2017). In disaster-prone areas with steep or mountainous terrain, preserving existing woods and restoring damaged ones is critical. The vast woods of India's Western Ghats operate as a natural barrier against landslides and soil erosion (Narendra, 2012).

Buffer against heavy rain: Forests absorb and slow down precipitation, acting as a buffer during heavy rainfall. This lowers the likelihood of soil saturation and conse- quent landslides (Merk, 2020). The thick vegetation of Germany's Black Forest exam- amplifies the protective effect of forests in minimizing the impact of excessive precipitation on mountainous environments.

Community engagement: Community engagement in forest conservation and sustainable land use practices is typically required for successful landslip mitigation. Community-based reforestation programs in Nepal's landslide-prone areas illustrate the need to incorporate local populations in the preservation and management of forests for disaster resilience (Pandey, 2018).

- **Nature-Based Solutions for Agricultural Landscapes**

Agroforestry and terracing techniques

Soil erosion control: Agroforestry uses trees and shrubs in agricultural environments, bringing several benefits. Tree roots aid in the binding of soil particles, hence avoiding erosion. Terracing is the process of building step-like structures on slopes to reduce the speed of water flow and soil erosion (Morgan, 2009). Terracing is used to counteract soil erosion and increase agricultural output in nations such as Ethiopia, where the Tig- ray region's watershed management scheme incorporates terracing (Molla, 2017).

Enhanced soil fertility: Agroforestry methods also promote soil fertility by encouraging nutrient cycling. Trees and crops in agroforestry systems frequently have complementary growth patterns, avoiding nutrient competition. The incorporation of nitrogen-fixing plants, as in traditional Southeast Asian agroforestry systems, improves soil fertility and preserves agricultural output (Kris, 2017).

Wetland agriculture and buffer zones

Flood mitigation: Wetland agriculture is the cultivation of crops in flood-prone locations. Wetlands operate as natural flood barriers, absorbing excess water. The ancient practice of floating gardens in wetland areas in Bangladesh enables families to adapt to annual monsoon floods while maintaining agricultural livelihoods (Haseeb, 2008) Water purification: Wetlands act as natural filters, purifying water by trapping sediments and filtering contaminants. Wetland buffer zones serve to protect these vital ecosystems. The Everglades Agricultural Area in Florida, USA, for example, has constructed buffer zones to decrease agricultural runoff and protect the health of the Everglades wetlands (Lomeu, 2022).

Livelihood support: Wetland agriculture not only helps flood resilience and water purification, but it also offers communities sustainable livelihoods. The Vietnam- ese Mekong Delta relies on wetland agriculture for rice farming, demonstrating the need to integrate agriculture with wetland ecosystems (Berg, 2016).

Soil health management

Sustainable practices: Soil health management involves employing sustainable agriculture methods such as cover cropping, crop rotation, and low tillage. These measures improve soil structure, nutrient availability, and water retention (Saha, 2012). The adoption of conservation agricultural methods in the Midwest of the United States helps sustain soil health and resilience in the face of harsh weather events (O'neill, 2021).

Drought resistance: By conserving moisture and fostering robust root systems, healthy soils are more equipped to endure the effects of drought. Agroecological approaches, as observed in portions of Sub-Saharan Africa, assist farmers in building resilient soil ecosystems, lowering crop sensitivity to drought conditions (Fisher, 2015).

- **Nature-Based Solutions in Climate Resilience**

Climate change adaptations

Adaptation strategies: Nature-based solutions (NBS) are critical in assisting communities in adapting to the effects of climate change. Restoring natural wetlands to improve flood resilience in coastal regions is one example, as proven by the restoration of the Humber Estuary salt marshes in the United Kingdom (Ducrotoy, 2010)

Community engagement: Community participation and local knowledge are frequently required for successful climate change adaptation through NBS. In Nepal, for example, community-managed forestry programs allow local populations to adapt to changing climatic circumstances while increasing biodiversity (Pandey, 2018).

Carbon sequestration and climate mitigation

NBS, such as reforestation and afforestation, considerably contribute to carbon sequestration, hence reducing climate change. The Bonn Challenge, a global endeavor to re-forest and reforest damaged lands, aims to trap carbon while encouraging sustainable land use. Large-scale reforestation projects, such as the African Forest Landscape Restoration Initiative (AFR100), aim to reforest 100 million hectares of African land by 2030. These initiatives not only aid in carbon sequestration but also biodiversity conservation and long-term development (Armani, 2022).

2.2 Successful NIS projects for DRR

- **Water management of the Netherlands**

The Netherlands has achieved worldwide recognition for its extremely successful water management system, notably in handling flood and storm surge concerns. To develop a comprehensive and robust water management system, the government successfully utilized a combination of Nature-Based Solutions (NBS) and modern engineering structures. One of the most important components of the Dutch method is the use of an integrated water management plan that integrates both natural and manmade solutions. This approach recognizes the value of collaborating with the natural landscape to im- improve resilience. Floodplains are critical components of the Netherlands' water management policy. By allowing controlled flooding in selected locations during high water levels, the country decreases the danger of its principal dikes being overwhelmed and offers additional storage space for excess water (Van, 2016). The Netherlands' large network of dikes and levees protects low-lying communities against floods. To ensure the effectiveness of them, these structures are precisely constructed and routinely maintained. The Delta Works project, which was started in the aftermath of the terrible North Sea Flood of 1953, is a prime illustration of the country's dedication to dike construction and coastline protection. The Delta Works includes sophisticated storm surge barriers such as the Oosterscheldekering and the Maeslantkering. These barriers are intended to be activated during extreme storm surges to protect vulnerable coastal regions from flooding. The Maeslantkering, in particular, is an outstanding moveable storm surge barrier that closes automatically during severe weather. The Netherlands employs a polder system, in which low-lying regions surrounded by dikes are purposefully preserved below sea level. Pumping stations are installed in Polders to drain surplus water, therefore generating arable land and minimizing flood danger. This system is a one-of-a-kind hybrid of man-made infrastructure and natural water management (Peter–Jules, 2006). The Netherlands is rapidly modifying its water management policies to meet the difficulties posed by climate change. This includes continued infrastructure expenditures, research, and the development of new ways to deal with increasing sea levels and higher precipitation. Recognizing the worldwide scope of wa- ter-related issues, the Netherlands actively participates in international cooperation. Dutch organizations and specialists contribute to initiatives all around the world, facilitating knowledge sharing and assisting other nations in developing resilient water management techniques (Van, 2007). Ultimately, the Dutch water management method combines Nature-Based Solutions with modern engineering to produce a strong defense against floods and storm surges. This comprehensive plan, characterized by adaptability- city and international collaboration, establishes the Netherlands as a global leader in creative and effective water management.

- **The coastal defense strategies of the U.S.A**

To successfully reduce coastal disasters, the United States employs an array of Nature- Based Solutions (NBS). This comprehensive strategy includes the strategic utilization of salt marshes and mangroves, as well as a variety of other nature-based treatments. With their distinctive flora and dynamic ecosystems, salt marshes provide natural barriers against storm surges and coastal erosion (Reguero, 2014). These marshes provide vital habitat for a wide range of flora and wildlife while also functioning as a protective barrier, absorbing and dissipating wave energy during storms. Mangroves, with their complicated root systems, play an important part in coastal defense. These ecosystems serve as natural storm-surge barriers, stabilizing sediments and reducing coastline erosion. Mangroves contribute to biodiversity and the general health of maritime ecosystems in addition to their protective role (Elizabeth, 2022). In addition to salt marshes and mangroves, the United States employs a variety of additional Nature-Based Solutions. Living shorelines combine natural vegetation and oyster reefs to safeguard coastal regions, while dune restoration programs use native vegetation to stabilize dunes for increased storm resistance (Garland, 2015). Beach nourishment refers to the process of replacing degraded beaches with sand or sediment (La, 2022). Seagrass meadows help to safeguard coastlines by lowering wave energy and stabilizing sediment, whilst oyster reef restoration operations build natural breakwaters. Wetland restoration projects expand beyond salt marshes to include freshwater and estuary wetlands that operate as storm surge barriers. Natural barrier islands provide vital storm buffers, and their maintenance is critical for coastal defense. Furthermore, green infrastructure in urban settings, such as green roofs and permeable pavements, helps to manage rainwater and minimizes the danger of urban floods. This diversified array of Na- ture-based Solutions, when combined, represents a comprehensive and ecologically benign plan for improving coastal resilience in the United States. The combination of protecting natural habitats like salt marshes and mangroves and developing green infrastructure demonstrates a multidimensional strategy that not only protects against coastal disasters but also promotes the general health of coastal surroundings (Phillippe, 2023).

- **Restoring the Loess Plateau in China**

The Loess Plateau restoration project in China is an excellent illustration of the beneficial results that may be obtained by using Nature-Based Solutions (NBS). This effort has been extremely beneficial in controlling soil erosion while also improving local livelihoods (Li, 2021). The Loess Plateau, known for its delicate ecology and vulnerability to erosion, faced substantial environmental issues, such as the loss of rich topsoil and decreased water retention capacity. In response, the restoration project put in place a variety of NBS centered on sustainable land management methods. Afforestation activities, the construction of check dams, and the creation of terraced farms are all important parts of the Loess Plateau restoration project. Planting trees and bushes to stabilize the soil and prevent erosion was referred to as afforestation. Check dams were carefully constructed to decrease soil erosion, limit water flow, and promote water retention. Terraced fields aided in the regulation of water flow, the prevention of soil erosion on slopes, and the increase of agricultural yield. The project's positive effects go beyond environmental advantages (Jin, 2011). Local people's livelihoods have improved as a result of greater agricultural output, improved water availability, and the development of new revenue streams such as eco-tourism. The restoration efforts have shown that NBS can achieve a healthy balance of environmental protection and social growth. In conclusion, the Loess Plateau restoration project in China exemplifies how Nature-Based Solutions may efficiently solve environmental concerns (Li, 2021).

3. Current limitations and prospects for NIS in DRR

Current limitations Financial and Policy barriers

Limited funding: One of the most significant problems in implementing Nature-Based Solutions (NBS) for Disaster Risk Reduction (DRR) is a lack of financial resources. Adequate finance is required for NBS project development, implementation, and sustainability. In certain circumstances, the initial expenses of nature-based therapies may be viewed as prohibitively expensive, discouraging investment (Datola, 2023).

Inadequate Policy Support: The lack of supporting policies or the presence of contradictory rules might hinder NBS implementation. Governments and organizations must develop clear policies that encourage and support the incorporation of nature-based techniques into disaster risk reduction programs (Young, 2019).

Land Use Conflicts and Stakeholder Engagement
Conservation and development conflicts: NBS frequently requires reconciling conservation efforts with developmental goals, resulting in land use disputes. To strike a balance between protecting natural ecosystems and addressing the needs of urbanization or agriculture, considerable thought and effective conflict resolution solutions are re- required (Udo, 2023).

Stakeholder Engagement: It is critical to include stakeholders such as local communities, NGOs, and enterprises. Effective communication and collaboration may aid in the formation of consensus and the resolution of issues. Involving local people in planning and decision-making processes, for example, can result in more sustainable and socially acceptable NBS results (Pagano, 2019).

Long-term monitoring and maintenance
Challenges of Sustainability: Ensuring the long-term efficiency of NBS needs continual monitoring and maintenance. However, sustainability issues, such as a lack of resources or institutional capability, might jeopardize the long-term viability of these initiatives. Case example: In locations where rainwater collection is being used as an NBS, continual maintenance is crucial to preventing system failures. Sediment accumulation or structural damage can develop if the system is not cleaned and repaired regularly, limiting the system's capacity to reduce flooding and maintain water supplies during dry seasons (Yildirim, 2021).

3.2 Future Prospects Scaling up NIS Globally
Scaling up Nature Inspired Solutions (NIS) for Disaster Risk Reduction (DRR) requires international cooperation. Sharing information, experience, and resources on effective NBS implementation helps improve community resilience across the world. Initiatives such as collaborative research initiatives and multinational collaborations promote the sharing of best practices and new solutions.

Synergies with Sustainable Development Goals (SDGs)
NBS is strongly aligned with several Sustainable Development Goals (SDGs), demonstrating its ability to solve interrelated social concerns. Afforestation initiatives, for example, not only help disaster resilience by limiting soil erosion, but they also meet SDGs relating to climate action, biodiversity protection, and poverty reduction. Recognizing and exploiting these synergies increases NBS's appeal and effect.

International Corporation
International cooperation is critical for the global advancement of NIS. Sharing information, experiences, and successful case studies may help countries. Collaboration platforms, such as worldwide conferences, research networks, and capacity-building efforts, are critical in establishing a common knowledge of the efficacy of NIS in a variety of circumstances. This collaboration means

that experiences learned in one place may inspire efforts in another, resulting in more resilient and flexible DRR techniques.

4. Conclusion

In conclusion, the review article highlights definitions, current trends, successful projects, limitations, and prospects of implementing Nature-Inspired Solutions (NIS) in Disaster Risk Reduction (DRR). The worldwide trend towards sustainability has resulted in the implementation of innovative NIS across several areas, proving their efficacy in minimizing natural disaster impacts. Successful NIS projects, such as the Netherlands' water management system, the United States' coastal defense strategy, and China's restoration of the Loess Plateau, demonstrate the concrete benefits of incorporating nature-based techniques. However, obstacles such as budgetary limits, legislative gaps, and the requirement for long-term maintenance have restricted wider implementation. Global collaboration is crucial for maximizing future opportunities. Scaling up NIS necessitates international collaboration, information exchange, and capitalizing on synergies with the SDGs. Overcoming present constraints includes collecting funds, implementing supporting legislation, resolving land-use issues through stakeholder participation, and assuring NIS project sustainability. Finally, the research highlights the potential of NIS in improving catastrophe resilience and contributing to long-term development. Addressing obstacles and developing international collaboration will pave the path for a more resilient and adaptable disaster risk reduction in the future.

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SUSTAINABLE TRANSPORT

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DEVELOPMENT OF A TRANSPORTATION SUSTAINABILITY RATING SYSTEM FOR ROAD CONSTRUCTION PROJECTS IN SRI LANKA

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Abstract: To encourage sustainable development in transport infrastructure, several Transportation Sustainability Rating Systems (TSRS) have been developed by different organizations around the world. However, Sri Lanka lacks a rating system in place for this purpose. Thus, this study aims to develop a TSRS to evaluate the sustainable performance of road construction projects in Sri Lanka. Initially, globally recognized existing TSRSs such as the Civil Engineering Environmental Quality Assessment and Awards Scheme (CEEQUAL), Envision, and Greenroads were critically analyzed together with GreenSL for transport infrastructure to identify their advantages and adoption. According to the outcomes, Greenroads was found to be more like the GreenSL for transport infrastructure rating system which is under development by the Green Building Council of Sri Lanka. Therefore, Greenroads and GreenSL were used to evaluate a case study project to evaluate the effectiveness of the GreenSL for the transport infrastructure rating system. Further, a questionnaire and several discussions were conducted with industry experts to obtain improvement suggestions for the GreenSL for the transport infrastructure rating system as well as the relative weights therein. The results of the case study show that the GreenSL for transport infrastructure rating system is effective in terms of Relevance, Measurable, and Uniqueness but less effective in terms of Reliability. The GreenSL for transport infrastructure rating system was developed as a 100-point scoring system including suitable sustainability indicators and weightings. Future studies can further improve this proposed rating system by incorporating emerging sustainability of best practices in its rating structure.

Keywords: Sustainability; Sustainable development; Transport infrastructure; Rating systems; Sri Lanka

1. Introduction

The construction industry has been identified for its activities leading to environmental issues, including the overuse of global resources in both construction and building operations, as well as pollution of the surrounding environment (Ding, 2008). The industry is actively seeking sustainable construction methods that can minimize emissions, energy consumption, resource usage, and negative impacts on the natural environment. Green buildings that incorporate sustainable materials and consume fewer resources and energy during their life cycles are being proposed through numerous research and development works from all around the world. Further, through the implementation of green building rating systems, efforts have been made to assess the performance of such green buildings in terms of energy and resource consumption, and impacts on the environment, while considering the social and economic impacts of such buildings. As a result of this, the construction sector is making proactive movements towards achieving sustainable goals.

The construction sector is not limited to buildings. The transport sector involves many large-scale constructions such as roads and bridges which may also contribute to substantial damage to the environment during both construction and operational periods. The stakeholders in the sector have identified the importance of prioritizing and advocating for sustainability in the construction and maintenance of current and future projects (Litman and Burwell, 2006; Clevenger *et al.*, 2016a). Like green building rating systems, the transport industry has also developed several rating systems during the past decades. Envision, Greenroads, and GreenLITES are some rating systems adopted in developed countries. These are specifically designed to evaluate the sustainability of roadway development. These rating systems are based on earlier research that emphasized the importance of incorporating sustainable performance metrics not only for transportation mobility but also for the design and construction of transportation facilities. Contextual and technological differences between developed and developing countries demand a careful review of such measures before their adoption by developing countries. This research attempts to review existing rating scales and develop a transportation sustainability rating system that can evaluate the sustainable performance of road projects in Sri Lanka.

2. Literature Review

2.1 Sustainability in the Construction Industry

The concept of sustainability has become increasingly important in every industry all over the world (Hubbard and Hubbard, 2019). The primary goal of sustainability is to maintain economic prosperity and a good standard of living for everybody while safeguarding ecological systems (Muench, Anderson, and Bevan, 2010). Efforts towards sustainability are built on three key pillars environment, society, and economy which are named as the triple bottom line.

The construction industry has become a larger contributor to environmental pollution, climatic changes, waste, and resource degradation (Park and Ahn, 2015). The construction industry attempts to achieve sustainability based on a holistic approach spanning across the project life cycle. Thus, sustainability is achieved in different stages of design, construction, operation, maintenance, and demolition (Park and Ahn, 2015; Diaz-Sarachaga *et al.*, 2016). According to (Chang and Tsai, 2015; Griffiths, Boyle, and Henning, 2018), considerable efforts to adopt sustainability concepts for construction projects were made in the 1990s and 2000s and they specifically focused on building construction. Consequently, several sustainable rating systems such as LEED (Leadership in Energy and Environmental Design) in the US, BREEAM (Building Research Establishment Environmental Assessment Method) in the UK, and CASBEE (Comprehensive Assessment System for Building Environmental Efficiency) in Japan were developed to evaluate the sustainability of building constructions (Chang and Tsai, 2015). These rating systems help the stakeholders to identify green practices and assess progress towards sustainability. However, they have become less successful in road construction (Park and Ahn, 2015; Szpotowicz and Tóth, 2020)

2.2 Sustainable transport infrastructure

Afrin and Yodo (2020) mention that due to traffic congestion, there are additional costs for extra hours traveled and extra energy used. As a result, congestion occurs with many social, economic, and environmental impacts. As Dhakap and Schipper (2005) describe many of the challenges associated with urban transportation are focused on energy use.

The transport sector has been associated with higher levels of emissions. According to Rakitskaya (2021), the transport sector has been identified as the second-largest source of CO_2 emissions globally, and the contributor of 1/4th of total energy-related CO_2 emissions. Transport emissions grew at an annual average rate of nearly 1.7% from 1990 to 2021, faster than any other end-use sector. These highlight that transport sectors have substantial levels of emissions at the operational level. On the other hand, such transport facilities would also be associated with some unsustainable practices during their construction stage as well. Although road construction is a great investment for a country, it consumes a substantial amount of resources and generates a colossal amount of waste (Sarsam, 2015). Though it seems the negative impact is only on the environment, the influence will be there for society and the economy of the country as well (Griffiths, Boyle, and Henning, 2018). These calls for research work on sustainability in road construction.

Park and Ahn (2015), define a sustainable transport infrastructure as a system that can enhance mobility and improve the standard of living of the users while protecting the environment. This definition has further been reinforced by (Bueno, Vassallo, and Cheung, 2015) stating that a transportation infrastructure becomes sustainable when it fulfills the transportation needs of a particular society and contributes to the economic development of the country by protecting natural laws and human values.

2.3.The necessity of transportation sustainability rating systems

With many researchers identifying the absence of sustainability rating methods for infrastructure projects, the sustainability evaluation criteria were gradually introduced to infrastructure projects starting in 2000 (Fernández-Sánchez and Rodríguez-López, 2010; Matar *et al.*, 2017). This has resulted in several sustainability rating systems to evaluate the sustainable performance of infrastructure projects (Szpotowicz and Tóth, 2020). Various countries have developed different transportation sustainability rating systems (TSRS) and these have been adopted to evaluate different road construction projects (Clevenger *et al.*, 2016b).

Further, as per the review by Park and Ahn (2015), a green rating system facilitates Baselining, Benchmarking, Prioritization, decision support and selection, and Documentation. Additionally, green infrastructure rating systems provide advantages for various stakeholders for internal sustainability performance evaluation, procurement, and specification, for determining which projects are sustainable to allocate funds to, for developing sustainable policies, and for specifying sustainable road construction methods (greenroads.org, 2018).

2.4.Existing green rating systems

Infrastructure projects are more complex in nature and may vary significantly in scale and scope. Different systems are available for buildings and structures, infrastructure projects, and communities. A proper understanding of the existing green rating systems would benefit project developers, donor agencies, consultants, contractors, and government agencies in selecting a green rating system that suits the circumstances of their decision-making process. Although (Wijewantha and Kulatunga, 2022) describe a rating system for expressways, still Sri Lanka lacks a TSRS that can evaluate every kind of road project (Hapuarachchi and Jayawickrama, 2017). This paper attempts to address such research gap by,

- Reviewing the existing systems in terms of basic details, nature of projects, the scope of sustainability categories, and detailed indicators
- Developing a green rating system for road projects in Sri Lanka

3. Research Aim

This research aimed to develop a transportation sustainability rating system for road construction projects in Sri Lanka with below specific objectives.
Objective A: Propose a suitable set of indicators for a TSRS in Sri Lanka
Objective B: Propose a set of weights to reflect the relative importance among indicators used for TSRS

4. Methodology

4.1. Objective A: Selection of a TSRS: GreenSL

Through an extensive literature review of several existing TSRS, for their representation of key evaluation aspects parameters of GreenSL were identified as a potential set of parameters. However further improvements to this were made using a case study evaluation using GreenSL. The case study project was also evaluated using the Greenroads rating system which is the most frequently used internationally.

4.2. Objective A: Evaluation of a case study project using indicators of GreenSL and Greenroads

The evaluation of a real-life project for sustainability using Greenroads and GreenSL rating systems was conducted, and the areas of improvement were discussed. A Rehabilitation/Improvement rural road project under the purview of the Provincial Road Development Department-Northwestern Province was selected. The project was assessed based on the documents, construction drawings collected from the Provincial Road Development Department-Northwestern Province, the information gathered from the discussion carried out with the Executive Engineer, and the site visit. If the project met any of the specified criteria outlined in the manual, it received the assigned marks; otherwise, it was scored zero. The manuals of Greenroads and GreenSL rating systems which include the rating structure of these rating systems were used to conduct the sustainability rating. As these manuals contained the goals and the requirements that should be satisfied by the project to be sustainable, the project was evaluated by using the manuals.

4.3. Objective A: Effectiveness for indicators of GreenSL

Using three of the commonly used effectiveness evaluation parameters (Relevance, Measurability, Reliability, and Uniqueness) for an indicator. The evaluation of the effectiveness of indicators of the GreenSL rating system was evaluated**.** This was done based on the challenges faced during the case study evaluation. Based on the outcomes of the above evaluation, the GreenSL rating system was improved by adding sustainability indicators.

4.4. Objective B: Development of relative weights for indicators of GreenSL

The relative weights of the indicators were obtained based on the ratings obtained through a questionnaire survey distributed among the experts in the road sector. Participants rated each sustainability indicator using a three-point Likert scale for their importance (1- Not important at all, 2- Somewhat important, and 3- Highly important). 80 road sector experts voluntarily participated in a Google questionnaire and among them, the response of 55 experts who had more than 2 years of experience in road construction were used to develop the weights. The mean rating value of each indicator was evaluated and the ratio among mean values was used to derive the relative weights. Based on the outcomes steps, the requirements that should be satisfied by a project to achieve the points of the rating systems were decided and a complete rating structure was then developed.

5. Results and Discussion

5.1. Objective A: Indicator parameters of GreenSL and its effectiveness

The ratings achieved by the case study project for GreenSL and Greenroads are given in Table 1.

Table 1: Sustainability ratings for case study project using the Greenroads and GreenSL rating systems

Greenroads		**Green SL**	
Sustainability Criteria	**Points**	**Sustainability Criteria**	**Points**
Environment & Water (EW)	3	Mobility For All (MFA)	2
Construction Activities (CA)	7	Transportation Planning (TP)	0
Materials & Design (MD)	3	Energy and Atmosphere (EA)	2
Utilities & Controls (UC)	0	Materials and Resources (MR)	5
Access And Liveability (AL)	4	Environmental Impacts (EI)	6
Creativity And Effort (CE)	0	Community Impacts (CI)	1
		Innovation Design (ID)	0
Total Points Earned (Out of 130)	**17**	**Total Points Earned (out of 100)**	**16**

As per the scores, the project has scored low total scores from both rating systems. Being a rural road, the project scored zero or some components that reflected creativity and planning. Scores for these parameters would be available for urban roads or expressways.

Reliability: A TSRS should be able to assess the entire project's sustainability by considering every aspect that affects sustainability. The rating process revealed that GreenSL did not cover sustainability indicators such as Soil management, Habitat conservation, Electric vehicle infrastructure, Power energy reduction, Emergency access, Health and safety impact analysis, and an Educated and integrated project team. This aspect of GreenSL's reliability should be improved to increase its ability to assess the sustainability performance of every aspect of a project. GreenSL should improve its reliability by incorporating the above aspects.

Measurability: The sustainability aspects included in a rating system should not be subjective. Therefore, the rating criteria should be able to express sustainability in measurable terms. During the rating, the GreenSL rating system was able to measure the sustainability of different sustainability best practices, based on the assigned weights. Hence, GreenSL was found to be effective in terms of measurability.

Relevance: A TSRS is expected to employ suitable concepts for evaluating project sustainability. GreenSL has satisfied relevance since all included sustainability indicators are related to the evaluation of various best practices relevant to road construction projects.

Uniqueness: Rating systems are expected to give credit to unique/ innovative practices. GreenSL has given due consideration to these since it has emphasized 'bicycle facility design,' allocating 6 out of 100 points, which is a distinctive approach aimed at promoting cycling as a transportation mode in Sri Lanka. Another unique feature is the inclusion of 'Community involvement' not just as a sustainability indicator but as a prerequisite in its rating structure. This ensures community engagement in project planning and design, as well as active participation in project improvement efforts. Based on the above several indicators were added to GreenSL namely Multi modes of transportation, Soil management, Habitat conservation, Electric vehicle infrastructure, Power energy reduction, Emergency access, Health, and safety impact analysis, and an educated and integrated project team.

5.2. Objective B: Derivation of importance weights

The weights of importance for each main indicator and sub-indicator are given in Table 2.

Table 2: Weights of importance

Indicator (Main/ sub)	Relative weight among indicators	
	Among sub-sustainability Indicators	**Among main indicators**
Mobility for all (MFA)		**0.143**
Multi modes of transportation	0.178	
Transit facilities	0.170	
Bicycle facility design	0.160	
Pedestrian facility design	0.163	
Pathway lighting and design	0.160	
Conflict points	0.169	
Transportation planning (TP)		**0.152**
Parking facilities	0.168	
Optimum level of service	0.156	
Travel time and fuel usage reduction	0.179	
Responsive traffic signals	0.172	
Emergency access	0.157	
Intelligent transportation systems	0.168	
Energy and atmosphere (EA)		**0.142**
Lighting energy efficiency	0.143	
Infrastructure energy efficiency	0.145	
Electric vehicle infrastructure	0.143	
Fossil fuel and emission reduction	0.143	
Paving emission reduction	0.142	
Power energy reduction	0.149	
Volatile organic compounds	0.135	
Resources and Materials (RM)		**0.142**
Lifecycle costing	0.201	
Responsible siting	0.188	
Recycled content	0.198	
Long-life pavement designs	0.208	
Local materials	0.205	
Environmental impacts (EI)		**0.146**
Soil management	0.199	

Stormwater management	0.222	
Water-efficient landscaping	0.203	
Reflective pavement design	0.186	
Habitat conservation	0.190	
Community Impacts (CI)		
Community involvement	0.163	
Health and safety impact analysis	0.185	
Noise mitigation plan	0.168	**0.137**
Traffic noise reduction	0.170	
Light pollution reduction	0.159	
Aesthetical visual elements	0.155	
Innovative ideas and efforts (IIE)		
Educated and integrated project team	0.340	
Innovative ideas	0.333	**0.138**
Exemplary performance	0.327	

Transportation planning had the highest weight among all main indicators while Community Impacts and Innovative ideas and efforts received the lowest. However, the relative importance of the main indicators did not differ much from each other.

Among the six sub-sustainability indicators of Mobility for all, modes of transportation had the highest weightage, and the lowest importance was obtained by both Bicycle facility design and Pathway lighting and design although the differences among these were not substantial.

According to the results of the second main indicator Transportation planning, Travel time, and Fuel usage reduction have obtained the highest importance while the Optimum level of service shows the lowest importance. For the main indicator Energy and atmosphere highest ranking was received by Power energy reduction while Volatile organic compounds were ranked the lowest. Long-life pavement designs received the highest relative weight while Responsible siting for the sub-sustainability indicators for Resources and materials. Concerning the primary sustainability indicator, Environmental impacts Stormwater management had the highest importance, while Reflective pavement design was deemed the least important. According to the results for the main indicator Community impacts, Health and safety impact analysis has obtained the highest and Aesthetic visual elements had the lowest. The educated and integrated project team received the highest rating under the main indicator of Innovative ideas and efforts.

To improve the sensitivity of the rating structure of the TSRS, industry experts have suggested several sub-sustainability indicators. The respective main and sub-sustainability indicates are, Mobility for all - Facilities for differently abled people; Transportation planning - Carpooling system and Overtaking bays; Energy and atmosphere - Solar power for streetlights and Energy audit; Resources and materials - Quality/durable materials; Responsibility guarantee from designers and contractors; Environmental impacts - Wastewater management and Less paved areas; Community impacts - Rehabilitation of people, Local employment; Innovative ideas and efforts- Research funding

5.3. Ddevelopment of Modified GreenSL Transportation Sustainability Rating System

5.3.1. Rating Structure

Based on the relative weights among main indicators and sub-sustainability indicators, the final weights for each indicator were calculated. Based on this points to be assigned for sub-sustainability indicators were developed as given in Table 3. Further, explanations were developed to guide the assignment of points under each category based on previous experience and literature. In addition, the prerequisites were also added appropriately.

Table 3: Modified GreenSL for transport infrastructure rating system

Mobility for all (MFA)		**14.3 Points**
MFA 1	Multi modes of transportation	2.6 Points
MFA 2	Transit facilities	2.4 Points
MFA 3	Bicycle facility design	2.3 Points
MFA 4	Pedestrian facility design	2.3 Points
MFA 5	Pathway lighting and design	2.3 Points
MFA 6	Conflict points	2.4 Points
Transportation planning (TP)		**15.2 Points**
TP Prerequisite 1: Level of service		
TP Prerequisite 2: Safety audit		
TP Prerequisite 3: Traffic maintenance plan		
TP 1	Parking facilities	2.6 Points
TP 2	Optimum level of service	2.3 Points
TP 3	Travel time and fuel usage reduction	2.7 Points
TP 4	Responsive traffic signals	2.6 Points
TP 5	Emergency access	2.4 Points
TP 6	Intelligent transportation systems	2.6 Points
Energy and atmosphere (EA)		**14.2 Points**
EA 1	Lighting energy efficiency	2.0 Points
EA 2	Infrastructure energy efficiency	2.1 Points
EA 3	Electric vehicle infrastructure	2.0 Points
EA 4	Fossil fuel and emission reduction	2.0 Points
EA 5	Paving emission reduction	2.0 Points
EA 6	Power energy reduction	2.1 Points
EA 7	Volatile organic compounds	2.0 Points
Resources and Materials (RM)		**14.2 Points**
RM Prerequisite 1 – Construction waste management		
RM 1	Lifecycle costing	2.9 Points
RM 2	Responsible siting	2.6 Points
RM 3	Recycled content	2.8 Points
RM 4	Long-life pavement designs	3.0 Points
RM 5	Local materials	2.9 Points
Environmental impacts (EI)		**14.6 Points**
EI Prerequisite 1 – Pollution prevention		
EI 1	Soil management	2.9 Points
EI 2	Stormwater management	3.3 Points
EI 3	Water-efficient landscaping	3.0 Points
EI 4	Reflective pavement design	2.7 Points
EI 5	Habitat conservation	2.8 Points
Community Impacts (CI)		**13.7 Points**
CI Prerequisite 1 – Community outreach		
CI 1	Community involvement	2.2 Points
CI 2	Health and safety impact analysis	2.5 Points
CI 3	Noise mitigation plan	2.3 Points

CI 4	Traffic noise reduction	2.3 Points
CI 5	Light pollution reduction	2.2 Points
CI 6	Aesthetical visual elements	2.1 Points
Innovative ideas and efforts (IIE)		**13.8 Points**
IIE 1	Educated and integrated project team	4.7 Points
IIE 2	Innovative ideas	4.6 Points
IIE 3	Exemplary performance	4.5 Points
TOTAL POINTS		**100**

5.3.2.Certification Thresholds

Under this rating system, a project can obtain a maximum of 100 points. By referring to past literature, four certification thresholds and awards (Figure 10) were proposed.

- All prerequisites + 40% to 49% of the total marks – Bronze
- All prerequisites + 50% to 59% of the total marks – Silver
- All prerequisites + 60% to 69% of the total marks – Gold
- All prerequisites + 70% or over of the total marks – Platinum

Figure 1: Certification levels of the proposed rating system.

6. Conclusions

The major outcome of this research was the development of a TSRS for Sri Lanka to evaluate the sustainability performance of road construction projects. The case study results show that the GreenSL transportation sustainability rating system, which is being developed, is effective in terms of Relevance, Measurability, and Uniqueness. However, it is less effective in terms of Reliability. Therefore, to enhance the effectiveness of the rating system modifications were carried out. Based on the results of the questionnaire survey, the relative weights for indicators and sub-sustainability indicators were developed. In this study, the effectiveness of the GreenSL rating system was evaluated using only one case study project and it can be identified as a limitation of this study. More case studies are recommended to find out any other limitations.

7. Future directions

This proposed rating system includes the sustainability best practices used in the current road projects. The sensitivity of the proposed transportation sustainability rating system can be further enhanced by future research by integrating emerging sustainable best practices around the world. Further, future work can expand this into different systems specific to road class.

Acknowledgment

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A PRICING POLICY FOR VEHICLES AND FUEL FOR SRI LANKA

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Abstract: Sri Lanka is facing an economic crisis, alongside congestion and emissions problems in its central commercial city hubs. The lack of a properly connected public transportation system has exacerbated these issues. Fuel pricing and vehicle pricing are critical policy factors in addressing transportation challenges. However, the effectiveness of current transport sector pricing in solving these problems remains uncertain. In recent years, the Sri Lankan government implemented measures such as a fuel pricing formula and tax concessions for electric and hybrid vehicles. However, the observed demand patterns for petroleum fuel do not indicate that the desired objective has been achieved, revealing inefficiencies in ad-hoc government decisions. This research examines existing fuel and vehicle pricing policies in Sri Lanka, comparing them globally while proposing more rational and development-based pricing policy recommendations. The specific research objectives include a global policy review and designing a pricing policy tool. The significance of this research lies in its usefulness in addressing the urgency of improving public transportation, addressing congestion pollution, and reversing the economic downturn in Sri Lanka. Global pricing strategies for fuel and vehicles reveal valuable insight for a scientific approach to fuel and vehicle pricing through outcome-based taxation, including promoting environmentally responsible practices and reducing dependence on imported goods.

Keywords: Fuel pricing; Vehicle pricing; Transportation; Policy analysis; Policy tool

1. Introduction

1.1 Background of The Research

Transportation, in essence, encompasses the conveyance of individuals and commodities. Its evolution is closely linked to advancements in global technology and research and development efforts, progressing from slower methods such as carts to rapid modes exemplified by high-speed trains like the Shinkansen. Transportation can be categorized into three primary domains: maritime, aviation, and land. All these modalities are fundamentally reliant on fossil fuels to power the moving entities, commonly referred to as vehicles (Rodrigue, 2020a). Vehicle and fuel pricing are vital to achieving sustainable mobility by reducing travel-related issues. Policies are crucial for sustainable transport.

1.1.1 Fuel and Vehicle Pricing

The final retail price of fuel varied among different types of fuel varieties. Gasoline and Diesel are refined from crude oil, which is extracted from the ground. Therefore, the fuel pricing of Gasoline and Diesel is influenced by the price of crude oil. The crude oil price fluctuates due to many reasons, such as the influence of OPEC, supply and demand factors, natural disasters, political instability, and exchange rates.

The vehicle pricing process is affected by internal factors such as manufacturing costs, including labor, research and development, engineering, and production expenses. Further external factors such as supply and demand, consumer preference, and competition among vehicle manufacturers affect vehicle pricing. Economic conditions, including inflation rates, exchange rates, and interest rates, are some of the factors that influence vehicle pricing (Rodrigue 2020c). For both fuel and vehicles, there is no particular static method to decide pricing. It depends on the transport policies of a specific country. For example, consider a country that focuses on reducing CO_2 emissions; it can focus on reducing taxes on Electric vehicles. On the other hand, countries that manufacture vehicles may lower their final prices.

1.1.2 Sri Lanka

As per the Sri Lanka Sustainable Energy Authority (2020), around 1/3 of the total energy is consumed by transportation. From that also around 98.5% accounts by road transportation. Fuel holds the highest percentage of Sri Lankan annual expenditure. It was 15.82% of merchandise imports in 2021(Trading Economics, 2023) out of the total fuel consumption for transportation is used for passenger transportation. Out of that, around 82% is operated by a private vehicle, while the rest is used for public transit (Kumarage, 2022).

The abundant vehicle usage creates massive traffic congestion, leading to many problems such as waste of productive work hours and emissions to the environment. Thus, it is evident that it is required to take a step to reduce the mode share of a private vehicle. Proper scientific policy implementation is needed for that. The government can intervene in this effort in three significant ways. They are fuel pricing, vehicle pricing, and road user charging. Road user charging in Sri Lanka will be complex, and fuel and vehicle taxing will be much more effective as both fuel and vehicles are significant imports of Sri Lanka. There is a fuel and vehicle taxing system in Sri Lanka. But the problem is how far they are aligning with sustainable goals.

1.2 Research Objectives

The main aim is to research global fuel and vehicle pricing policies and provide some options for a rational development-based pricing policy for fuel and tax policy for motor vehicles in Sri Lanka.

In addition to the main objectives, the following are the other focused objectives.

- Conducting a global policy review based on fuel and vehicle pricing.

- Design of policy tool to determine the impact of fuel and vehicle pricing on vehicle ownership and use.

2. Literature review

2.1 Introduction

Fuel and vehicles play a critical role in the human life. People consume fuel and vehicles to fulfill their transportation requirements. In the global transportation context, fossil fuel is used around 80% currently (Fossil Fuels | EESI 2021). Petroleum is the abundantly used fossil fuel type in transportation. In 2021, 90% of the total energy use of the transportation sector in the USA is accounted for by petroleum products.

Air pollution, global warming, acid rain, and climate change are some of the problems unavoidable due to the consumption of fossil fuels. In addition to that, traffic congestion has become a significant issue in the world. India, China, and the USA are reputed for higher traffic and road congestion (Harrou *et al.*, 2022). Policy intervention is required to reduce traffic congestion. Fuel pricing, vehicle pricing, and road user charging or congestion charging can be identified as effective policy interventions in reducing traffic congestion (Harrou *et al.*, 2022; Naqvi *et al.*, 2020). Seoul, South Korea; Santiago; Chile, Tokyo; Japan; and Madrid, Spain, are some of the best public transportation systems around the world, where it has become the most affordable mode to commute (International TEFL Academy, 2023). Countries like Hong Kong, Singapore, and some of the EU countries have utilized vehicle and fuel pricing to mitigate traffic congestion and emissions(Unidas 2003). Further, there are motivations such as tax concessions and subsidiaries for alternative vehicles as well. Therefore, it is evident that transportation policymaking plays a critical role in mitigating congestion and emissions.

These discussed concerns prevail in Sri Lanka to a certain extent. There is also an economic impact because both fuel and vehicles are imported. Several types of transportation policies can be identified in the history of Sri Lanka. As per the National Transport Commission (2017), the objectives have been set up to accessible transport systems, energy efficiency, environmental protection, increased safety & security, and positive contribution to the economy. On the other hand, Sri Lanka annually spends more than 1000 billion rupees on road transportation. Among them, more than 50% accounts for fuel and vehicle & spare part imports(Kumarage 2020).

2.2 Review of Pricing Methods and Models

The pricing of fuel and vehicles in the automotive and energy sectors relies on the utilization of various pricing methods, models, and frameworks (Delsalle, 2002). This section critically examines the existing literature to comprehensively understand these approaches and their relevance in analyzing pricing dynamics. Through a review of previous studies, we gain insights into the different methodologies employed in the field.

Table 1: Pricing Approaches

Approach	Description
Econometric Approach	Utilizes statistical and mathematical techniques to analyze historical data and estimate relationships between pricing factors, focusing on their impact on demand and supply. Allows quantification of the effects of pricing changes on consumer behavior and market dynamics.
Optimization Approach	Relies on mathematical models to derive the optimal pricing strategy by considering specific objectives and constraints. Enables organizations to make data-driven decisions regarding pricing, leading to improved financial performance.
Cost-Benefit Approach	Involves evaluating costs and benefits associated with various pricing decisions. Assesses financial implications based on factors such as production costs, revenue potential, consumer surplus, and societal welfare.

2.3 Variables Affecting Fuel and Vehicle Pricing

The cost of fuel and vehicles is influenced by a wide range of interrelated variables that affect the dynamics of the market in Sri Lanka (Samaratunga, 2014). It can be learned a lot about the intricate mechanisms that control fuel and vehicle pricing in the Sri Lankan market by examining factors like fuel supply and demand, economic conditions, political and policy influences, vehicle manufacturing and supply, consumer preferences, and environmental considerations. A thorough analysis of these elements can lead to a deeper comprehension of pricing dynamics, which is advantageous to industry stakeholders and decision-makers.

Table 1: Factors Affecting Fuel Pricing

Feature	**Description**
Fuel Supply and Demand	The balance of supply and demand determines fuel prices. Factors include global oil prices, refining, distribution, and government subsidies. Understanding this balance is essential.
Economic Factors	Economic conditions impact prices. Factors include exchange rates, GDP, taxes, and other costs affecting fuel and vehicle pricing.
Political and Policy Factors	Political stability, government policies, and subsidies shape fuel and vehicle market dynamics, e.g., tax incentives for electric vehicles.
Vehicle Manufacturing and Supply	Global vehicle pricing depends on manufacturing and supply. In Sri Lanka, import costs and assembly components influence prices.
Consumer Demand and Preference	Consumer behaviour, financing options, competition, and preferences influence vehicle prices. Dealers consider customer demand.
Environmental Factors	Environmental concerns, like emissions and pollution, affect pricing. Sri Lanka implements policies like the SLVET program to address these issues.

The existing body of research on gasoline and car pricing in Sri Lanka has identified some gaps and limitations, underscoring the need for further study. These gaps include a limited focus on the socioeconomic effects of pricing dynamics, a lack of investigation into the environmental effects, the significance of exploring the impact of technological advancements, an understanding of the role of government policies and regulations, a sense of consumer preferences and behaviours, and an examination of regional pricing disparities. Additional studies in these areas would significantly advance our knowledge of Sri Lanka's gasoline and car pricing while addressing the gaps in the body of existing information. By bridging these gaps, researchers can shed light on the broader socioeconomic effects, evaluate the environmental impact, examine pricing variations across different regions, analyze the influence of technological advancements, and assess the effectiveness of governmental policies. Such research initiatives will ultimately broaden the body of information and educate researchers, industry stakeholders, and policymakers, enabling more informed decision-making and the creation of successful strategies in Sri Lankan fuel and vehicle pricing.

3. Methodology

3.1 Overview

The methodology section plays a crucial role in research as it outlines the systematic approach employed to achieve the research objectives. In this study, the aim is to investigate global fuel and vehicle taxing policies and provide options for a rational development-based pricing policy for fuel and tax policy for motor vehicles in Sri Lanka.

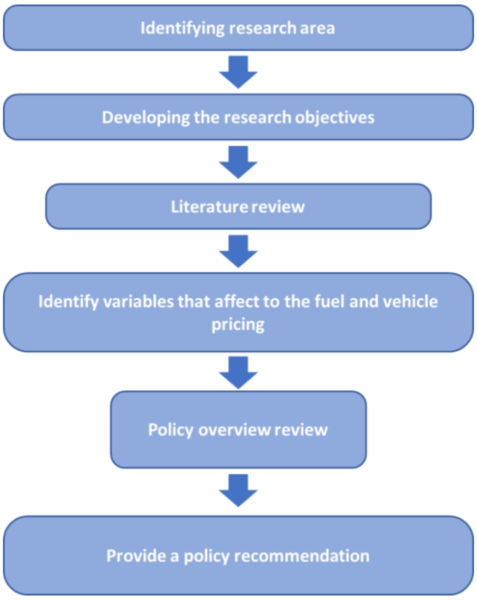

Figure 1: Overview of the Methodology.

3.2 Global Policy Review

To gain a comprehensive understanding of the research context, an extensive review was conducted, focusing on relevant policies and regulations related to fuel and vehicle pricing. A Thematic approach is used to perform the policy overview, considering around ten countries that are proclaimed as having comparatively sustainable transportation systems.

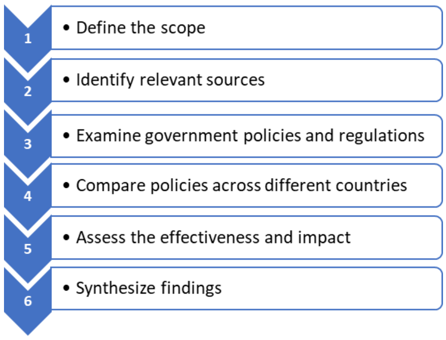

Figure 2:Process of policy review.

3.3 Providing design of a policy tool

The design for the policy was developed after conducting a comprehensive global review of transportation policies and an in-depth historical analysis of fuel and vehicle consumption in Sri Lanka. Therefore, this formulation of pricing for fuel and vehicles will help to achieve this goal by appropriately playing with relevant components of taxing fuel and vehicles scientifically.

4. Discussion

4.1 Policy Review of Sri Lanka

Many people and goods movements in Sri Lanka happened through road transport mode. The inefficiencies of the Sri Lankan railway, which continuously faced losses from 1947, clearly depict the inefficiencies in policy deployment of the Sri Lankan transport sector. As per the Ratnasabapthy, 2018), Policy constraints, including government wage policies and pricing limitations, contributed to the financial strain.

Some governments have made some efforts to implement sustainable practices. In the 2018 budget, Sri Lanka proposed a shift to non-fossil fuel vehicles by 2040, aiming to convert all government vehicles to hybrid or electric by 2025 (Deloitte Sri Lanka, 2017). but the concern is the progress of these targets is whether Sri Lanka has achieved the due progress by present in 2023. This highlights the issue of policy discontinuation. On the other hand, the government decided to provide vehicle loans at a 4% interest rate in 2014, which resulted in an increased usage of private vehicles.

Further, an initiative like the SLVET program initiated in 2013 is successfully operating, though there are some loopholes. In addition to that, a technical committee of experts provided 8 recommendations to improve the fuel quality, which was on the discussion table during the high economic crisis in 2013 (Sugathapala, 2015). They are as follows.

- Introduction of premium-quality fuels nationwide.
- Formulation of a comprehensive fuel quality roadmap.
- Exploration of the viability of integrating Liquefied Natural Gas (LNG) as an energy source across all energy sectors.
- Alignment of fuel quality standards with emission standards (both mobile and stationary sources) and ambient air quality standards.
- Implementation of the proposed Expansion and Modification of the existing refinery at Sapugaskanda.
- Establishment of an independent fuel quality testing laboratory.
- Provision of Euro IV Standard Fuel throughout the country
- Creation of a Fuel Quality Management Committee.

Except for the provision of Euro IV Standard Fuel, all the other recommendations have not been achieved yet after 10 years. Thus, it is evident that though Sri Lanka has implemented good transport policy initiatives, there is more space to be developed further.

4.2 Global Policy Overview

The policy overview was conducted by referring to available literature and publications. A set of countries has been selected by considering the availability of reports, publications, and various policy interventions. Further selected countries are reputed for the proper transportation policies.

The following are the selected countries for policy review.

1. Switzerland
2. Japan
3. Germany
4. United States
5. Netherlands
6. Singapore
7. South Korea
8. China
9. India
10. Australia

Table 2: Comprehensive Summary of Policy Review

Country	Focus of Transportation Policies	Vehicle Pricing Policies	Fuel Pricing Policy
Switzerland	Sustainable mobility, multimodal transport system, promoting cycling and walking, improving public transportation, reducing emissions, enhancing safety and efficiency	High vehicle registration tax, incentives for EVs	Influenced by international oil prices, transportation costs, and taxes.
Japan	Technological advancements, efficient and reliable transportation, promoting electric vehicles and charging infrastructure	Weight-based acquisition tax, incentives for eco-friendly vehicles	Regulated by the government, influenced by international oil prices, exchange rates, and taxes. Implements price adjustments based on market conditions for stability and affordability.
Germany	Public transportation, cycling infrastructure, pedestrian-friendly urban planning, renewable energy in transportation, reducing congestion, integrating different modes of transport	CO2-based registration tax, incentives for EVs	Includes international oil prices, taxes, and distribution costs. Taxes are based on energy content and environmental impact.
United States	Multimodal approach, connectivity, accessibility, infrastructure development, modernizing public transit systems	Market-driven pricing, federal tax credits for EVs	Determined primarily by market forces, with variations across states and regions. There is no national fuel tax system, and states impose individual fuel taxes for infrastructure funding.
Netherlands	Sustainable transport, promoting cycling, efficient public transportation, compact cities, reducing car usage, promoting electric vehicles and charging infrastructure	Progressive tax based on CO2 emissions, EV incentives	Influenced by international oil prices, taxes, and distribution costs. Significant fuel taxation, including excise duties and value-added tax (VAT), to promote sustainable transportation.
Singapore	Integrated transport system, road pricing mechanisms, smart mobility solutions, promoting electric vehicles and charging infrastructure, efficient land use	Vehicle quota system, high taxes, incentives for EVs	Determined by a managed market system with fuel taxes. Taxes are adjusted periodically based on market conditions and government objectives. Factors in import prices, transportation costs, and margin.
South Korea	Public transportation, smart transportation systems, promoting electric vehicles, sustainable transport mobility	Progressive tax based on engine size and emissions, EV incentives	Influenced by international oil prices, taxes, and distribution costs. Fuel taxes are used to fund infrastructure projects and environmental initiatives. Varies based on fuel type and energy content.
China	Infrastructure expansion, high-speed rail, urban metro systems, promoting electric vehicles, vehicle emission standards	Consumption tax, subsidies for EVs, city-based restrictions	Regulated by the government, sets a price ceiling considering international oil prices, exchange rates, taxes, and other factors. Managed pricing system with fuel subsidies to support sectors.
India	Infrastructure improvement, enhancing connectivity, promoting electric vehicles, developing charging infrastructure	GST, registration fees, incentives for EVs	Influenced by international oil prices, taxes, and distribution costs. Varied taxes across states. Implemented dynamic pricing mechanism for retail fuel prices based on market conditions.

Australia	Efficient and sustainable mobility options, road safety measures, intelligent transport systems, equitable access to transportation services	Market-driven pricing, regional EV incentives	Determined by market forces with variations across states and regions. Includes fuel taxes such as excise duties and goods and services tax (GST) for government revenues and infrastructure funding.

4.2 Design for a policy tool

A schematic or a design for a policy tool had been suggested based on findings and learnings from global policy review and literature review. Policy Design can be described as the systematic process of developing effective methods to address complex societal, environmental, and economic challenges (Mukherjee *et al.*, 2021). In that process, clear objectives must be established, the environment must be assessed, key change levers must be identified, potential impacts must be quantified, policy options must be considered, cost-benefit analyses must be performed, stakeholders must be involved, the policy tool must be implemented, and its effectiveness must be monitored and evaluated (Errida and Lotfi, 2021). This systematic approach aids in the creation and application of policies that can lead to the intended results and enhance well-being.

The following steps are designed after a proper study to follow in implementing a policy.

1. **Defining the objective-** Objectives refer to the outcomes or specific goals that a policy targets to reach.
2. **Assess Current Situation**- This involves collecting and analyzing the relevant information to understand the actual situation of the country.
3. **Identify the key levers-** Deciding the factors that can be affected by policy amendments is the critical focus of this step.
4. **Quantify the impact-** Measuring or calculating the potential effects of the different policy implications is required in this stage.
5. **Consider policy options**- Examining the different policy options available to achieve the particularly desired objectives is majorly done with the learnings and findings of the previous steps.
6. **Cost-benefit Analysis-** Evaluation or assessment of cost and benefits related to every decided policy option is done in this stage.
7. **Engage with relevant stakeholders**- Engage with relevant stakeholders such as government agencies, fuel suppliers, vehicle manufacturers, and consumer groups. Seek their input, address concerns, and build consensus around the proposed policy tool.
8. **Policy Implementation-** Develop a roadmap for implementing the chosen policy tool, including a timeline, resource allocation, and monitoring mechanisms. Consider the necessary legislative changes, administrative procedures, and public awareness campaigns.
9. **Monitor and Evaluate-** Continuously monitor the implementation and impact of the policy tool. Evaluate its effectiveness in achieving the desired objectives and make necessary adjustments as needed.

The policy tool part is associated with steps 3, 4, 5, and 6 (Identify the key levers, Quantify the impact, Consider Policy Options, and Cost and benefit Analysis). The proper calculations with the related actual data will provide a realistic understanding of the impacts of the policy decision.

Table 3: An example of a Policy Tool Draft

1	Define the Policy Objective						
2	Assess Current Situation						
3	Identify Key Levers	fuel prices, taxes, incentives, vehicle standards, or infrastructure development					
4	Quantify Impact	fuel consumption	CO2 emissions	other relevant parameters			
				Congestion	accidents	travel time	Govt expenditure/ Revenue
5	Consider Policy Options						
6	Conduct Cost-Benefit Analysis	Fuel Saving	CO2 emission reduction	Other relavant parameters			
				congestion redcution	accidents reduction	Travel time saving	Govt net gain

Following is a demonstration of how the above tool can be utilized.
Objective: Ban the importation of fossil fuel vehicles and exclusively allow electric vehicles from 2024.

Assessing the current situation and identifying the key leverages is an essential and complex step that is required to conduct.
Quantifying the Impact:
Annual impact includes:

- 5-10% reduction in fuel consumption
- 7-15% decrease in CO_2 emissions
- 15-20% increase in congestion in major cities
- 5-10% reduction in travel time
- 5-15% increase in government expenditure for transportation sectors, with a 10-15% boost in revenues

Policy Options:

- Increase taxation on fossil fuels
- Raise operational costs, including registration fees for fuel vehicles
- Enhance incentives for electric and hybrid vehicles
- Invest in developing charging infrastructure
- Implement a proper vehicle scrappage system

Cost-Benefit Analysis:

- Benefits in environmental and social aspects outweigh economic gains.
- The policy objective appears sustainable.
- Proceeding requires a well-planned strategy, including revenue recovery measures to facilitate the transition and address the public accustomed to existing practices.

After proper evaluation, policy implementation should be done, and continuous monitoring and evaluation should be done.

5. Conclusion

This study delves into the intricacies of fuel and vehicle pricing policies, focusing on Sri Lanka's transportation challenges. The analysis of global policies and the proposed policy tool offers a comprehensive perspective for crafting effective strategies. Sri Lanka's transportation inefficiencies, notably in the railway sector, underscore the urgency for comprehensive reforms. While the 2018 budget set ambitious goals for non-fossil fuel vehicles, sustained progress, and policy continuity remain critical. The global policy overview highlights diverse approaches, from Switzerland's sustainable mobility focus to China's consumption tax and EV subsidies, offering valuable lessons for Sri Lanka.

The designed policy tool, rooted in a systematic methodology, serves as a practical guide for balanced policy formulation. Emphasizing stakeholder engagement, continuous monitoring, and adaptive adjustments, the research aims to contribute to tangible improvements in Sri Lanka's transportation policies. In essence, this study aspires to bridge academic insights with practical policy development, fostering sustainable and efficient transportation in Sri Lanka. By synthesizing global experiences and tailoring strategies to local challenges, the research advocates for a transformative shift toward a more resilient and eco-friendly transportation landscape in Sri Lanka.

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SRI LANKAN VEHICULAR EMISSION ANALYSIS USING BIG DATA

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Abstract: Vehicular emissions pose a significant threat to environmental sustainability and public health in Sri Lanka, with the increasing number of vehicles on the roads exacerbating the problem. However, the lack of effective tools for measuring and managing emissions hinders effective policymaking in this area. This study aims to address this crucial issue by employing big data analytics to analyze vehicular emissions in Sri Lanka comprehensively. The study utilized a Vehicle Emission Test (VET) dataset spanning 2009 to 2020, comprising approximately 51 million data points. The data was thoroughly cleaned and pre-processed using Excel and R to ensure accuracy and reliability. To calculate CO_2 emission mass from vehicle exhaust gas, the equation proposed by Karunathilaka in 2018 was employed. The results revealed a consistent decrease in CO_2 emission mass per Liter of fuel consumed over time, indicating a positive shift towards more environmentally friendly vehicles. Diesel vehicles were found to emit lower CO_2 compared to petrol vehicles, aligning with global initiatives to mitigate greenhouse gas emissions. Additionally, the analysis highlighted the presence of intricate factors influencing CO_2 emissions beyond traditional metrics like mileage and vehicle age, emphasizing the need for further research. These findings have significant implications for theory, practice, and policy. They emphasize the importance of mitigating CO_2 emissions in the transportation sector and underscore the need for effective vehicular emission management, particularly in developing countries. The utilization of big data and advanced analytical tools can provide valuable insights into vehicular emissions and assist policymakers in making informed decisions to reduce the environmental impact of transportation. Overall, this research contributes to the pursuit of sustainable and greener practices within the transportation industry, facilitating a more sustainable and environmentally conscious future.

Keywords: Emission; CO_2; Air quality; Big Data; R Language; Regression

1. Introduction

Air pollution, a complex mix of particles, vapors, and gases from natural and human sources, undergoes chemical changes, forming substances like ozone and nitrogen dioxide (Gilmour et al. 2018). Urbanization, economic growth, and societal practices have amplified human-induced air pollution globally (Jiao et al. 2020), posing significant threats to human health, and the environment, and exacerbating global climate change. The burning of fossil fuels in high and middle-income nations and wood usage in low-income countries result in millions of annual deaths (Landrigan et al. 2018).

Monitoring air pollution is crucial for environmental justice, with certain regions, particularly those engaged in industrial activities, playing a significant role in emissions (Zhang et al. 2023). Tackling the complex challenges associated with improving air quality and mitigating the adverse impacts of pollution requires an interdisciplinary approach that integrates the fields of air pollution and emissions. By integrating these disciplines, we can better comprehend the multifaceted nature of the problem and develop comprehensive strategies to address it effectively. Emissions, the release of harmful substances into the atmosphere from stationary and mobile sources, are intrinsically linked to air pollution (European Environment Agency 2019). Reducing emissions is paramount to mitigating the detrimental consequences of climate change. Air pollution exposure has been linked to respiratory infections, cardiovascular disorders, cancer, and millions of fatalities worldwide (Ghorani-Azam et al. 2016). Certain populations, such as children, the elderly, and those residing in areas with high pollution levels, are particularly vulnerable to the adverse health effects of emissions (United States Environmental Protection Agency 2023).

Emissions also contribute to the alarming phenomenon of global warming and climate change. Greenhouse gases emitted by the combustion of fossil fuels, such as carbon dioxide, methane, and nitrous oxide, play a significant role in driving climate change (Shahzad 2017). Addressing air pollution aligns with the Sustainable Development Goals, which include initiatives to promote health, foster clean energy practices, drive industry innovation, develop sustainable infrastructure, and create resilient and sustainable cities and communities (Muñoz-Pizza et al. 2020). The multidimensional nature of air pollution and its complex interplay with global challenges are recognized, enabling us to strive toward a more sustainable and healthier future.

The combustion of fossil fuels stands as a significant contributor to atmospheric carbon dioxide emissions, with the transportation sector being the primary source of these emissions (International Energy Agency 2023). Vehicles emit a range of pollutants, including carbon monoxide, hydrocarbons, nitrogen oxides, sulphur oxides, and particulate matter, posing substantial environmental and public health challenges. Understanding the composition and impact of these emissions is pivotal for developing effective strategies to mitigate their adverse effects, fostering a cleaner and more sustainable future. Despite the alarming levels of air pollution, Sri Lanka lacks a comprehensive tool for measuring and managing vehicular emissions. This absence hampers accurate data collection, hindering evidence-based policy formulation and intervention strategies. The lack of a centralized platform also impedes the identification of emission hotspots, efficient resource allocation, and the evaluation of emission reduction initiatives. Bridging this research gap necessitates the development of a robust tool enabling real-time monitoring, data collection, and analysis. Such a tool would empower policymakers with precise information, facilitating evidence-based policy design, targeted interventions, and effective progress monitoring. Moreover, a centralized platform would enhance collaboration among stakeholders, fostering a coordinated approach to emission management in Sri Lanka. Addressing this gap in research would bolster endeavors to combat air pollution, devise sustainable strategies, and create a healthier environment for the population.

This research study aims to address the challenges presented by vehicular emissions through the utilization of big data analysis. Big data analytics has emerged as a potent tool for comprehending intricate phenomena and extracting invaluable insights from vast datasets. By harnessing the potential of big data techniques in vehicular emission analysis, we can deepen our understanding of emission patterns, ascertain the factors that contribute to these emissions, and develop innovative strategies to curtail and mitigate their impact. This research explores the possibilities that arise from the intersection of vehicular emissions and big data analytics to promote sustainable practices and foster a cleaner and healthier environment for future generations.

The geographic scope of this study is focused on Sri Lanka, enabling a detailed analysis of the country's transportation system and emission characteristics. The temporal scope covers the years 2017 to 2019, providing a multi-year perspective to understand emission trends and identify potential changes over time. The research specifically focuses on CO_2 emissions, a major greenhouse gas contributing to climate change and a key indicator of vehicular pollution.

The significance of this research study lies in its potential to address pressing environmental and societal concerns while advancing the Triple Bottom Line of sustainability. By focusing on vehicular emission analysis using big data, the study aims to contribute to reducing healthcare sector expenses associated with air pollution-related illnesses. This research encourages the development and implementation of a practical vehicle taxation system based on emission levels aiming to incentivize the adoption of cleaner vehicles and promote sustainable transportation practices. Furthermore, by curbing vehicular emissions, the research study aims to mitigate pollution levels, improve ambient air quality, and enhance the overall health of society. The study paves the path to empowering individuals by providing them with valuable information to make informed decisions when purchasing vehicles, allowing for brand and model comparisons based on emission levels. Addressing these significant aspects, the research study strives to create a cleaner, healthier, and more sustainable future for both the environment and society at large.

2. Literature Review

2.1. Air Quality and Transport Emission

Air quality is a critical factor in environmental preservation and human well-being. Maintaining acceptable air quality levels is essential for diverse ecosystems. Parameters such as temperature, relative humidity, oxygen levels, carbon monoxide concentrations, carbon dioxide levels, and particulate matter play a crucial role in ensuring optimal air quality (Prabhakaran et al. 2022). Air pollution is a complex mixture of particles, vapors, and gases originating from both natural and human activities. These pollutants can undergo photochemical reactions, leading to the formation of substances like ozone (O_3), nitrogen dioxide (NO_2), and secondary organic aerosols (SOA) (Gilmour et al. 2018). Anthropogenic air pollution has become a global concern due to increasing urbanization, economic growth, and social activity (Jiao et al. 2020).

Emission refers to the release of pollutants into the atmosphere from stationary and mobile sources, including smokestacks, structures, commercial establishments, and industrial facilities (European Environment Agency 2019). The urgent need to reduce emissions to mitigate the worst effects of climate change is widely acknowledged (Hannah Ritchie 2020). The effects of emissions and air pollution are inseparable due to their interconnectedness. Emissions have wide-ranging effects on living organisms, impacting human and animal health as well as the environment as a whole. Geographical conditions, global climate changes, and environmental differences influence human and animal health and the environment (Ghorani-Azam et al. 2016).

Vehicle emissions have a significant impact on air quality and contribute to environmental pollution and climate change. Automobiles are responsible for producing 80 to 90% of harmful emissions from various vehicles, with trains contributing 5 to 8%, air transport accounting for 1 to 2%, and marine transport contributing 1%. Despite improvements in engine technology and fuel efficiency, vehicle fuel consumption has increased severely over the past few decades (Sassykova et al. 2019). CO_2 emissions from various road transport modes, especially passenger cars, and trucks, have shown a discernible upward trend in the past two decades (Lyu et al. 2021). Several factors influence vehicle emissions. The manufacturer, vehicle model, emission standard, engine size, and fuel type used all play a significant role in emission levels (Davison et al. 2020). Real-world driving conditions, including driving patterns, traffic congestion, road gradients, cold start conditions, and ambient temperatures and pressures, significantly affect emissions. Real-world measurements capture a wider range of variability observed during actual driving, accounting for diverse driver behaviors, interactions with other road users, and interactions with highway infrastructure (Ahmad M.M. Khalfan 2017), Traffic congestion can lead to significantly higher emissions compared to road with no traffic (Wang et al. 2022).

In Sri Lanka, transportation, industry, and household activities are the primary sources of air pollution. Vehicle emissions account for over 60% of total emissions in Colombo, the capital city (Nandasena et al. 2010). Sri Lanka faces economic losses due to road traffic congestion and air pollution caused by a high number of vehicles on congested roads. The country's vehicle population is projected to increase, necessitating measures to address emissions and reduce pollution (Kumarage 2013).

2.2. Quantification Techniques Using Big Data

The emergence of big data is a result of the expansion of digital technologies and the increasing volume of data generated by these technologies (Acharya and Ahmed 2016). Big data refers to vast and complex data sets, often obtained from new and unconventional sources that are too large to be processed using traditional data processing tools. However, these extensive data resources present opportunities to address previously unsolvable business challenges (Oracle 2023).

Monitoring air pollution has emerged as an important environmental justice issue in recent years, particularly regarding the contribution of industrial regions and associated infrastructure to air pollutant emissions. Geographical studies highlight the importance of considering specific industrial land use boundaries when investigating air pollution (Zhang et al. 2023).

In Sri Lanka, no research integrated big data analysis to study vehicle emissions. This research employed the vehicle emission quantification equations proposed by a previous study by Konara in 2017 and Karunathilaka in 2018 (Konara et al. 2017; Karunathilaka et al. 2018). Combining those equations and big data analysis this research study quantifies the emission mass for every vehicle that goes through the vehicle emission testing process.

3. Methodology

The Vehicle Emission Test (VET) Program in Sri Lanka is a valuable data source for analyzing vehicle emissions. Two prominent approaches have been used in previous studies: stationary monitors and mobile sensors. Stationary monitors provide insights into air quality but do not provide precise quantification of vehicle emissions. Senarathna et al. used a mobile sensor on a police motorcycle to measure emission levels across different road segments in Kandy City. Both methods offer advantages but do not directly measure vehicle-specific emissions. The VET Program is crucial for research, providing valuable emission data specific to individual vehicles and contributing to a deeper understanding of the country's emission landscape.

The Vehicle Emission Test (VET) Program is conducted by two authorized entities, CleanCo and Laugfs. CleanCo operates 219 test stations across all 25 districts, capturing emissions data from a diverse range of vehicles. Laugfs operates 96 fixed stations and 143 mobile test stations, providing extensive coverage for emissions testing. This combination of fixed and mobile test stations allows for comprehensive data collection, ensuring a representative sample of vehicle emissions from various regions.

The utilization of CleanCo and Laugfs guarantees the reliability and accuracy of the collected data. The partnership between researchers and these entities fosters a collaborative effort to promote a better understanding of vehicle emissions and facilitate the formulation of effective policies to address environmental concerns. The dataset collected from CleanCo comprises approximately 33 million individual data points and spans the years 2009 through 2019. Laugfs' dataset consists of about 18 million data entries, covering the years 2016 through 2020. Figure 1 shows the data pre-processing and cleaning steps. These companies utilize gas analyzers, RPM meters, smoke opacity meters, moveable cameras, and temperature testing equipment to ensure a comprehensive and reliable evaluation of vehicle emissions, enabling a more nuanced understanding of the environmental impact of petrol and diesel vehicles.

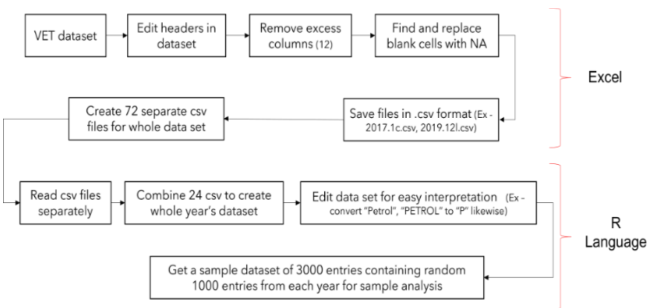

Figure 1: Data Pre-processing and Cleaning Steps.

4. Data Analysis and Results

An equation intended to measure CO_2 mass from the VET dataset is needed. A previous study has provided an equation to measure CO_2, CO, and HC masses using VET data (Konara et al. 2017; Karunathilaka et al. 2018).

$$M_i = V_{mix} \times Q_i \times C_i \tag{1}$$

$$CO_2 = 2.0110K\,(ppm\ \frac{v}{v}) \tag{2}$$

$$CO = 0.1162K\,(ppm\ \frac{v}{v}) \tag{3}$$

M_i - Mass emission of the pollutant i (CO, CO_2, HC) in g/l.
V_{mix} - Volume of attenuated exhaust gas expressed in m^3 per 1 liter and normalized to 293 Kelvins and 101.33 kPa.

Q_i - The density of pollutant i at standard temperature and pressure (293 K and 101.33 kPa) in kg/m^3.
C_i - Concentration of pollutant i in the diluted exhaust gas, expressed in ppm or (v/v) % and corrected by the concentration of pollutant i in the diluted air.

Equation 1 can be used to calculate the emission mass of specific pollutants (CO_2, CO, and HC) in vehicle exhaust gas. Equations 2 and 3 are employed to calculate the concentration of CO_2 and CO pollutants in the exhaust gas of diesel vehicles. Considering equations 1, 2, and 3, below 4 and 5 equations are used for quantifying CO_2 from both petrol (4) and diesel (5) vehicle emissions.

$$MCO_2 = 9.03 \times 1.842 \times F1AccCO_2 \tag{4}$$
$$MCO_2 = 15.81 \times 1.842 \times (2.0110 \times K_{avg}) \tag{5}$$

Table 1, 2, 3,4, and Figure 2, 3 show the mean CO_2 mass of petrol vehicles, the mean CO_2 mass of diesel vehicles, the highest F1AccCO_2 in 2017, and 2019, considering pass and fail vehicles, petrol motorcycle CO_2 emission mass, and diesel van CO_2 emission mass.

Table 1: Mean CO_2 Mass of Petrol Vehicles

	2017	2018	2019
Mean CO_2 Mass (P & F)	134.1 g/l	133.9 g/l	134.1 g/l
# of Vehicles (P & F)	4,613,317	4,917,183	5,516,102
Mean CO_2 Mass (Only P)	141.8 g/l	140.9 g/l	141.3 g/l
# of Vehicles (Only P)	3,316,404	3,765,612	4,311,647

Table 2: Mean CO_2 Mass of Diesel Vehicles

	2017	2018	2019
Mean CO_2 Mass (P & F)	58.9 g/l	52.6 g/l	46.0 g/l
# of Vehicles (P & F)	784,809	810,356	828,061
Mean CO_2 Mass (Only P)	28.5 g/l	27.5 g/l	25.8 g/l
# of Vehicles (Only P)	669,993	706,005	735,269

Table 3: Petrol Motorcycle CO_2 Emission Mass

Petrol Motorcycles			
Year	**Mean Mi**	**SD Mi**	**Count**
2017	129.0 g/l	40.8 g/l	2,059,992
2018	128.6 g/l	40.6 g/l	2,382,143
2019	130.5 g/l	40.0 g/l	2,791,730

Table 4: Diesel Van CO_2 Emission Mass

Diesel Van			
Year	**Mean Mi**	**SD Mi**	**Count**
2017	30.0 g/l	31.4 g/l	310,498
2018	29.3 g/l	30.8 g/l	326,074
2019	27.9 g/l	29.6 g/l	340,596

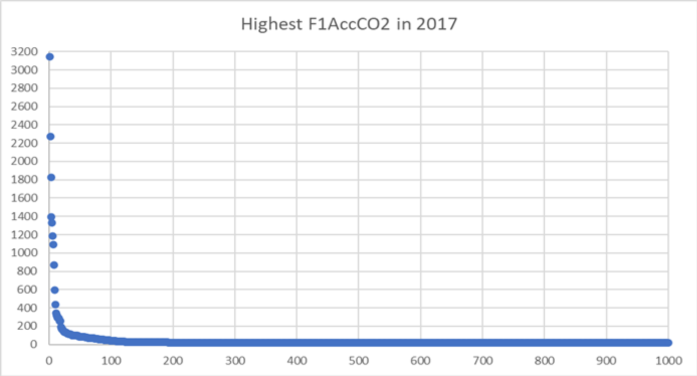

Figure 2: Highest F1AccCO2 in 2017 (P & F).

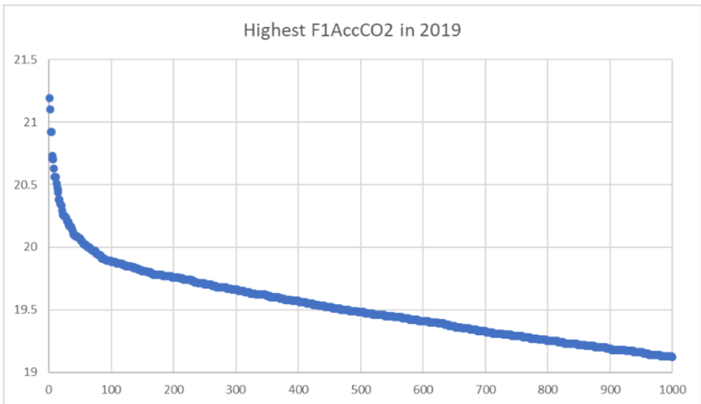

Figure 3: Highest F1AccCO2 in 2019 (P & F).

Regression analysis among CO_2 emission mass, mileage, and vehicle age did not indicate a strong relationship among those variables. Further analysis should be carried out to check other factors that influence the emission masses.

5. Discussion and Implications

According to Tables 1 and 2, the mean CO_2 mass for only-pass vehicles varies, 141.8 g/l in 2017, 140.9 in 2018, and 141.3 in 2019. The mean values for solely pass petrol vehicles show relative constancy, although a little volatility over time. From 2017 to 2018, 25,547 diesel-powered vehicles passed, and 17,705 passed in 2019. Diesel vehicle numbers have steadily increased over time. The mean CO_2 mass for solely passed diesel vehicles decreased from 28.5 g/l in 2017 to 27.5 in 2018 and 25.8 in 2019. Several variables explain this mean CO_2 mass decrease. First, heavy-duty, land, and diesel motor tricycles are driving diesel vehicle growth. Second, replacing older automobiles with newer, more fuel-efficient ones reduces mean CO_2 emission mass. Newer automobiles with better pollution controls replace older ones, lowering CO_2 emissions per vehicle.

The study faced several challenges and limitations, including limited data availability and reliability, extreme numbers, and a significant number of zero values. The K average column was also affected by these issues. Additionally, the district codes column was accidentally changed to a date type, making it difficult to analyze and explain the data. The linear regression model used in the study did not show a strong connection between variables and did not consider all factors affecting CO_2 mass emissions. To address these limitations and improve future research, researchers could add more recent years to the dataset, investigate the effects of policy changes and technology advances on CO_2 emissions, examine the effectiveness of current emission standards and policies, investigate the impact of different fuel types and vehicle fleet changes, and consider social and economic factors affecting car ownership and usage.

6. Conclusion

This research study aimed to quantitatively assess the mass of CO_2 emissions from vehicle exhaust gases, focusing on estimating the mean CO_2 mass for different fuel types and vehicle classes. The study also investigated the relationship between emission mass and vehicle variables such as meter and age using linear regression analysis. The findings showed a consistent increase in vehicle numbers across all classifications over time, indicating a growing vehicle population. However, there was a declining trend in CO_2 emission mass per liter of petrol consumed, indicating that newer vehicles are emitting less CO_2. Diesel vehicles also exhibited lower CO_2 emissions compared to petrol vehicles.

The study also found no significant correlation between CO_2 emission mass, mileage, and vehicle age, suggesting the existence of additional influential factors. The average CO_2 mass for petrol vehicles remained relatively stable over time, while diesel vehicles experienced a steady decline. The study also revealed the presence of intricate factors beyond mileage and vehicle age, requiring further research to understand their interplay. These findings can inform evidence-based policy decisions and technological advancements aimed at curbing CO_2 emissions from the transportation sector. Understanding and addressing the multifaceted aspects of CO_2 emissions are crucial steps toward a more sustainable and environmentally conscious future.

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