



ICRES
International Conference on
Resource Efficiency Towards Sustainability



Because Tomorrow Matters

The 02nd International Conference on

Resource Efficiency Towards Sustainability

“Resource Efficiency for a Resilient Future”



PROCEEDINGS BOOK

Editors

Prof. Ranjith Dissanayake | Dr. Pradeep Gajanayake | Eng. Sujith Gunawardhana



ICRES
International Conference on
Resource Efficiency Towards Sustainability

**International Conference on
Resource Efficiency Towards Sustainability**

**The 2nd International Conference on Resource Efficiency towards
Sustainability
(ICRES) 2026**

14th March 2026



Proceedings of the 2nd International Conference on Resource Efficiency towards Sustainability- (ICRES) 2026

VISION

To promote and accelerate the global transition towards a circular economy for sustainable and responsible resource management.

MISSION

To provide a dynamic platform for knowledge exchange, collaboration, and innovation that advances resource circularity and sustainability across industries.

All rights reserved. No part of this publication may be reproduced, stored in a retrieval system, transmitted in any form or by any means, electronic, mechanical, photocopy, and recording or otherwise, without prior permission of all the editors and conference chairs

ISSN 3121-4282

Published by: Graduate Associate Professional (Pvt) Ltd
Science Tower, 120/10A, Vidya Mawatha, Colombo 07

PREFACE

It is with great pleasure that we present the proceedings book for the 2nd International Conference on Resource Efficiency Towards Sustainability (ICRES) 2026, taking place on 14th March 2026. Building on the success and impactful discussions of the inaugural ICRES, this year's conference continues our commitment to advancing global conversations on resource efficiency, sustainable development, and the circular economy. As an extension of our extensive experience in organizing high-profile academic conferences, including the International Conference on Sustainable Built Environment (ICSBE), ICRES 2026 provides a platform for cutting-edge research and innovation in sustainable resource management across various disciplines. This program book reflects a collection of high-quality research papers and case studies that will be presented in parallel sessions, fostering meaningful interdisciplinary dialogues and collaborations. We extend our deepest gratitude to the distinguished keynote speakers for sharing their valuable expertise, helping us address the urgent sustainability challenges of our time. A heartfelt thanks also goes to the authors for their exceptional contributions and to the panel of academic and professional reviewers who have rigorously evaluated the manuscripts, ensuring their academic rigor. We are especially thankful to INSEE Ecocycle for their generous support and for hosting this conference, which has been instrumental in making ICRES 2026 a reality. We hope that this proceedings book will serve as an invaluable resource for researchers, practitioners, and policymakers engaged in sustainable resource management, and we eagerly anticipate the enriching discussions and collaborations that will emerge, guiding us toward innovative solutions for a more sustainable future.

Editors

Prof. Ranjith Dissanayake
Dr. Pradeep Gajanayake
Eng. Sujith Gunawardhana

The 2nd International Conference on Resource Efficiency towards Sustainability
14th March 2026 | Online

MESSAGE FROM THE CONFERENCE CO- CHAIRS

We are delighted to welcome you to the 2nd International Conference on Resource Efficiency Towards Sustainability (ICRES) 2026. This inaugural event brings together a global community of experts, innovators, and leaders committed to addressing the critical challenges of resource efficiency and sustainability in today's world.

The theme of ICRES 2026, Resource Efficiency Towards Sustainability reflects the urgent need for advancing solutions that balance human development with environmental stewardship. As we face an ever-growing demand for resources, it is imperative that we explore and implement strategies that promote sustainable resource use across all sectors.

The conference focuses on a broad range of topics that are key to advancing the agenda of sustainability, including advanced waste management technologies, the role of artificial intelligence in driving resource efficiency, the circular economy's role in urban planning, and the integration of life cycle assessment in industrial manufacturing. These discussions will provide invaluable insights for shaping future policies and practices in resource management, with a focus on reducing environmental impacts while fostering economic growth and societal well-being.

We extend our sincere gratitude to INSEE Ecocycle Lanka (Pvt) Ltd for their invaluable support as the host of ICRES 2026. Their commitment to sustainability and resource management has played a pivotal role in making this conference possible. Our heartfelt thanks go to the keynote speaker, authors, reviewers, and all those who have worked tirelessly to make this event a success. We look forward to the exciting exchange of ideas, the development of innovative solutions, and the collaborations that will shape a more sustainable future.

We trust that ICRES 2026 will inspire meaningful discussions, forge lasting partnerships, and contribute to the global effort in advancing resource efficiency and sustainability for generations to come.

Prof. Ranjith Dissanayake
Prof. Ajith De Alwis
Prof. Jose Arturo Garza-Reyes
Prof. Usha Iyer- Raniga
Eng. Sujith Gunawardhana

TABLE OF CONTENTS

PREFACE		ii
MESSAGE FROM THE CONFERENCE CO-CHAIRS		iii
 CIRCULAR ECONOMY IN MANUFACTURING AND INDUSTRIAL SYSTEMS		
ICRES26_022	OPTIMIZING EFFICIENCY IN DAIRY PROCESSING: A CASE OF A SET YOGHURT MANUFACTURING SECTION	1
ICRES26_059	POLYSACCHARIDE-BASED BIODEGRADABLE FILMS FOR RESOURCE-EFFICIENT PACKAGING: STRUCTURAL ENGINEERING, PERFORMANCE OPTIMIZATION AND SUSTAINABILITY PERSPECTIVES	15
ICRES26_060	VALORIZATION OF BIOMASS ASH FROM INDUSTRIAL WASTE AS A CIRCULAR FERTILIZER RESOURCE FOR SUSTAINABLE AGRICULTURE	30
ICRES26_076	PATH FROM AWARENESS TO BEHAVIOR IN THE ORGANIC FOOD MARKET: A NEW MODEL FOR SUSTAINABILITY IN THE CONTEXT OF CIRCULAR ECONOMY	40
 SUSTAINABLE RESOURCE MANAGEMENT AND URBAN DEVELOPMENT		
ICRES26_012	THE IMPACT OF CONSUMER PREFERENCES ON THE SUSTAINABLE DEVELOPMENT OF SRI LANKA'S HERBAL MEDICINE AGRO INDUSTRY: LOCALLY SOURCED VS. IMPORTED PRODUCTS	51
ICRES26_013	SOCIO-ECONOMIC IMPLICATIONS OF FAST-FOOD CONSUMPTION IN URBAN SRI LANKAN CONTEXT: EVIDENCE FROM WATTALA-MABOLA URBAN COUNCIL AREA	62
ICRES26_015	TECHNICAL ASSESSMENT OF WASTE-DERIVED PHASE CHANGE MATERIALS (PCMS) FOR COLD STORAGE APPLICATIONS IN RURAL AREA	79
ICRES26_021	CIRCULAR ECONOMY PRINCIPLES FOR ADAPTIVE REUSE OF COLONIAL BUILDINGS OF WORLD HERITAGE SITE: CASE STUDIES OF GALLE FORT	90
ICRES26_029	CONSUMER PREFERENCE DYNAMICS AND MARKET GROWTH POTENTIAL OF REGIONALLY BRANDED AGRICULTURAL PRODUCTS IN SRI LANKA: IMPLICATIONS FOR SUSTAINABLE REGIONAL DEVELOPMENT	108
ICRES26_030	INVESTIGATION OF INCORPORATION OF RECYCLED ASPHALT AGGREGATES IN RIGID PAVEMENTS IN SRI LANKA	115



ICRES26_044	VEGETATION DYNAMICS AS AN INDICATOR OF RESOURCE EFFICIENCY AND SUSTAINABLE URBAN PLANNING: A COMPARATIVE GIS-BASED STUDY OF SELECTED URBAN AND PERI-URBAN AREAS IN AMPARA DISTRICT, SRI LANKA	126
ICRES26_061	A GLOBAL REVIEW ON BIO-BASED SUPPLEMENTARY CEMENTITIOUS MATERIALS (SCMS) FOR SUSTAINABLE AND RESOURCE EFFICIENT CONCRETE	142
ICRES26_066	CONCRETE MATERIAL MODEL FOR PULVERIZED CONCRETE PARTICULATES	157

RESOURCE EFFICIENCY IN ENERGY, WATER, AND SUPPLY CHAINS

ICRES26_007	COMPARATIVE EVALUATION OF NATURAL MINERAL PHOTOCATALYSTS FOR SUSTAINABLE WASTEWATER TREATMENT USING MCDM APPROACH	167
ICRES26_057	AN EXPLAINABLE AI-BASED DECISION SUPPORT FRAMEWORK FOR DETECTING AND OPTIMIZING ENERGY RESOURCE INEFFICIENCIES IN COMMERCIAL BUILDINGS	176

CIRCULAR ECONOMY FOR INDUSTRY AND CLIMATE RESILIENCE

ICRES26_031	COST ESTIMATION BARRIERS IN THE ADOPTION OF CIRCULAR ECONOMY PRACTICES IN THE SRI LANKAN CONSTRUCTION INDUSTRY	190
-------------	--	-----

CASE STUDIES AND BEST PRACTICES IN CIRCULAR ECONOMY AND SUSTAINABILITY

ICRES26_020	CIRCULARITY IN CEMENT: INVESTIGATING THE USE OF BLAST FURNACE SLAG: A CASE STUDY	199
ICRES26_028	FISH MEAL VALUE CHAIN: AN INVESTIGATION ON CIRCULAR SOLUTIONS AND CHALLENGES IN SRI LANKA	208
ICRES26_041	A COMPARATIVE SUSTAINABILITY ASSESSMENT OF COSMETIC BOTTLE DESIGNS	223



ICRES

International Conference on
Resource Efficiency Towards Sustainability

**International Conference on
Resource Efficiency Towards Sustainability**

CIRCULAR ECONOMY IN MANUFACTURING AND INDUSTRIAL SYSTEMS

ICRES26_022

**OPTIMIZING EFFICIENCY IN DAIRY PROCESSING: A CASE OF A SET
YOGHURT MANUFACTURING SECTION****T.N.E. Liyanapathirana^{1*}, D.A.M. De Silva¹, A.S. Gunathunga²**¹*Department of Agribusiness Management, Faculty of Agricultural Sciences, Sabaragamuwa University of Sri Lanka*² *Leading Dairy Manufacturing Organization, Sri Lanka***Correspondence E-mail: thatsaraniel@gmail.com, TP: +94718917892*

Abstract: Efficient manufacturing processes are vital for transforming raw materials into finished products with minimal waste, reduced time, and optimized resource utilization. This study investigated the milk processing value stream for the set yoghurt products, focusing on a detailed analysis of value chain functions. It aimed to identify and quantify waste hotspots and assess inefficiencies within the production process. Based on the findings, targeted optimization strategies were recommended to enhance overall efficiency by reducing wastage. Data collection involved a combination of direct observations, interviews with machine operators, focus group discussions with cross-functional teams, and review of production records. Production activities across the set yoghurt production were systematically modelled using Value Stream Mapping (VSM) and detailed loss mapping techniques. Material losses were quantitatively assessed over a 12-month period through the application of descriptive statistics. The findings revealed that product mix wastage emerged as the most significant, consistently exceeding acceptable thresholds of key performance indicators. Waste hotspots were predominantly observed during batch startups, changeovers, and production end stages, with human errors and machine malfunctions further exacerbating inefficiencies. Instrumental to the reduction of these inefficiencies, proposed process improvement strategies include the provision of Brix refractometers, accompanied by operator training to ensure accurate usage, the development of comprehensive Standard Operating Procedures (SOPs) for batch changeovers, the introduction of visual management systems to enhance human accuracy, and machine enhancements, such as prioritizing and continuing preventive and autonomous maintenance for the set yoghurt filling machine, were identified as critical strategies to minimize material losses and optimize overall efficiency.

Keywords: Manufacturing Efficiency; Process optimization; Product Mix; Value Stream Mapping; Waste Hotspots

1. Introduction

Optimizing production efficiency and minimizing waste are critical for dairy manufacturers seeking to enhance their competitiveness within the industry. Waste in production encompasses any activities, time, or resources that do not contribute value to the final product (Karida, Treptow, & Windmark, 2023). Addressing inefficiencies and waste in the dairy processing industry is imperative for both economic and environmental reasons. Inefficient operations lead to increased costs, reduced competitiveness, and a negative impact on key performance indicators (KPIs). Key Performance Indicators (KPIs) are essential for assessing and tracking performance in industrial settings. They help pinpoint areas of inefficiency and highlight opportunities for improvement. KPIs can be applied at different levels, such as individual equipment, specific processes, or overall plant operations. (Lindberg et al., 2015).

Waste in dairy production, which includes product loss, energy inefficiency, and water wastage, represents a significant challenge that not only leads to higher operational costs but also negatively impacts sustainability goals. (Ramirez et al., 2006). Despite the recognition of these inefficiencies, there remains a gap in detailed studies examining the specific causes of waste and the strategies for addressing these issues within the dairy production sector. Minimizing waste is a crucial aspect of implementing lean production in manufacturing processes.

This research is mainly lie around a leading dairy manufacturer in Sri Lanka. The cultured products manufacturing section of this dairy plant was identified as a major source of inefficiency, with significant levels of waste impacting production costs and performance metrics. Key challenges included product mix losses during the transition from pasteurization to final product formation, as well as material wastage in packaging. These inefficiencies increased operational costs and adversely affected critical key performance indicators (KPIs), such as Yield Loss Percentage and Overall Equipment Effectiveness (OEE). The analysis of the Absolute Material Variance revealed that product mix wastage was the primary contributor to material loss within the plant. KPIs, such as Yield Loss Percentage and OEE, were crucial in evaluating and monitoring the plant's overall efficiency. Over the observed period, wastage levels consistently exceeded acceptable thresholds for these KPIs. Specifically, the Yield Loss KPI was exceeded in 11 out of 12 months, while the OEE KPI was surpassed in 7 out of 12 months, underscoring significant areas for improvement in operational performance. (Table1)

Table 1: Analysis of the Key performance indicators August to July

Key Performance Indicator (2023-2024)	Target	Average	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June	July
Yield loss %	0.72%	1.23	1.3	1.7	2.6	0.96	2.97	1.65	1.32	0.72	1.1	0.99	1.67	1.03
OEE	81.3%	78.64	74.6	68.0	71.4	72.80	74.68	82.28	82.22	73.11	82.21	82.24	82.29	82.29

Addressing these challenges required a systematic analysis of the production processes, including the identification of waste hotspots, root causes of inefficiency, and areas for improvement. The objectives of this research are to identify key stages and functions involved in the processed milk value chain, identifying primary waste hotspots located within the production process, and the magnitude of waste generated at these spots and to develop and propose strategies and recommendations for reducing wastage and improving efficiency.

2.1 Conceptual Framework

The conceptual framework of this study focused on analysing key variables to improve operational efficiency in cultured product manufacturing. Independent variables included value stream functions, comprising value-adding, essential non-value-adding, and non-value-adding activities, and specific types of waste, such as product mix, packaging material, fruit pulp, and machine downtime. Contributing factors to waste, including line losses, machine faults, and human errors, were also examined. These variables were analysed for their impact on the dependent variable, Overall Production Performance. This structured framework facilitated a comprehensive evaluation of the factors influencing manufacturing efficiency.

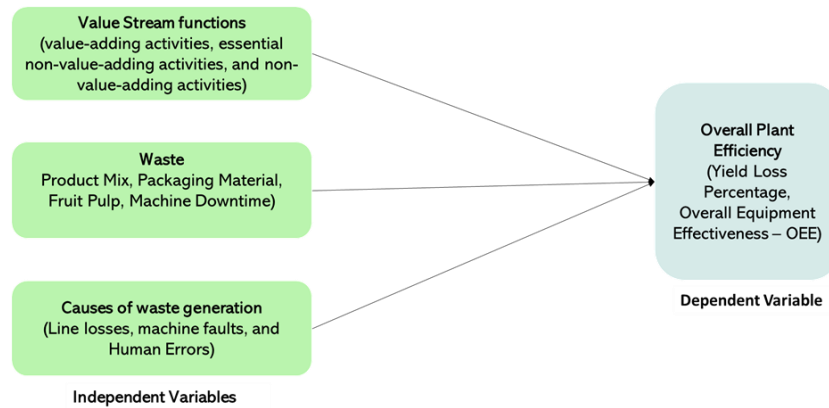


Figure 1: Conceptual Framework

2. Research Methodology

This study utilized a case study approach to analyse real-world practices in a dairy manufacturing facility, aiming to generate insights and support informed decision-making. Archival analysis of administrative records and surveys were incorporated to supplement data collection and provide a comparative perspective.

The facility produces set yoghurt, stirred yoghurt, drinking yoghurt, and set curd, with product mix wastage identified as the primary source of inefficiency, significantly affecting overall plant efficiency. "Product mix" refers to losses occurring between the mixing step and the final production stage. Purposive sampling was employed to focus on set yoghurt production, which accounted for the highest production volume and waste generation. The facility produces three set yoghurt varieties: two vanilla-flavoured and one strawberry-flavoured. Analysis of 12 months of production data confirmed set yoghurt as the most frequently produced product, followed by drinking yoghurt.

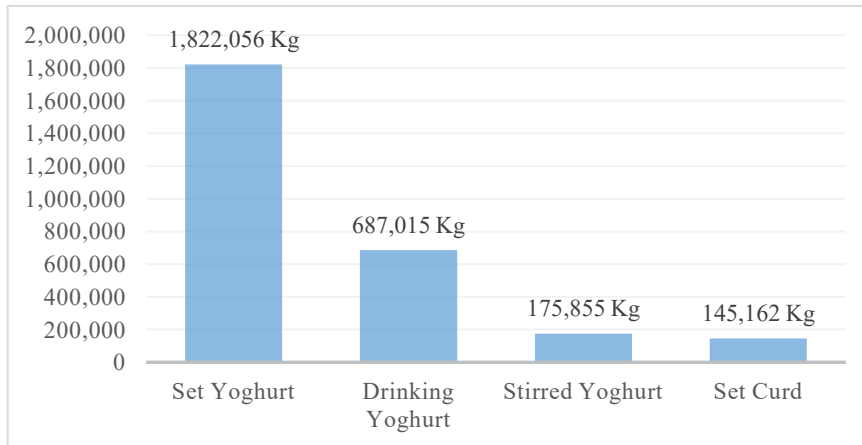


Figure 2: Total Product-Wise Production (in Kg) Over a 12-Month Period

2.2 Value Stream Development

The first objective involved analysing the milk processing value stream to classify key functions and identify waste generation points. Primary data were collected through direct observation and operator interviews, while secondary data were derived from Standard Operating Procedures (SOPs). Value stream map, developed from five production cycles per product, provided insights into the production chain, from raw milk unloading to final product preparation. This structured analysis facilitated the creation of lead time ladders and enabled targeted strategies to enhance efficiency and minimize waste.

2.3 Identifying and Quantifying Wastage

The second objective focused on identifying and quantifying waste across production stages. Secondary data, including 24-hour production records, SAP ERP reports, and material variance analyses, provided insights into plant efficiency and material wastage. Primary data from process observations identified specific waste types, such as product mix, fruit pulp, and packaging materials. Comprehensive loss maps were created to visually analyse waste hotspots and quantify wastage.

2.4 Root Cause Analysis of Inefficiency

The third objective involved uncovering root causes of waste and inefficiencies through in-depth interviews and focus group discussions with team members from engineering, food safety, quality, and production. Brainstorming sessions, cause-and-effect diagrams, and the "Five Whys" technique were employed to systematically identify underlying issues contributing to production inefficiencies.

2.5 Strategies for Waste Reduction and Efficiency Improvement

The final objective developed strategies to address inefficiencies through focus group discussions and benchmarking against industry best practices. Recommendations were formulated using insights from engineering, food safety, and production teams, along with secondary data.

2.6 Data Analysis

A mixed-method approach combined quantitative and qualitative techniques. Value stream maps were created using Microsoft Visio, and data from a 12-month period were analysed using IBM SPSS 25 and MS Excel 2016 to identify waste trends and quantify losses. Comprehensive loss maps were designed in Canva to visualize waste hotspots, while insights from interviews and focus groups informed cause-and-effect analysis and "why-why" evaluations.

3. Results and Discussion

A standard batch size for set yoghurt is 9,000 litres, and production typically involves four consecutive 9,000-liter batches. The cultured section produces three different set yoghurt varieties: two vanilla-flavoured lines and one strawberry-flavoured line. All three products are processed on the same production line using the same filling machine, with the primary difference being the ingredients added, such as the flavouring.

3.1 Value Stream Map

3.1.1 Information Flow

Using data and sales records collected from retailers, the Sales and Marketing and planning departments create a demand plan for the product. Based on this demand plan, the Planning department prepares a corresponding supply plan. Following the supply plan, the Procurement team places orders for ingredients and packaging materials from selected suppliers. There is also a dedicated Milk Procurement section responsible for sourcing raw milk in line with the supply plan, initiating the process with approved suppliers. Additionally, the Production Planning section creates weekly production plans to align with the supply chain. The SAP Enterprise Resource Planning (ERP) system is essential in managing the supply of ingredients, packaging materials, and bacterial cultures for production. It ensures that the right quantities are efficiently sourced from the stores, supporting the smooth flow of the production process. (Figure 2)

3.1.2 Material Flow

The production process for set yogurt begins with milk unloading, pasteurization, and cooling, followed by transfer to holding tanks after completing the CIP procedure. After a 20-minute waiting period, the mix is tested for quality, and starter culture is added, with another 20-minute waiting period before filling. The filling machine is then prepared, and the product is heated to 42°C, filled into cups, sealed, and transferred to the packing section. In the packing area, products are inspected, packed, and palletized before being sent for incubation. After incubation, products are stored in cold storage for seven days for quality testing. Once approved, the products are distributed to retail outlets.

3.1.3 Lead Time Ladder

The total production lead time is 11,305 minutes, with several key stages involved. These include 40 minutes for milk sample testing, 45 minutes for thermization, and 90 minutes for Cleaning-in-Place (CIP). The mixing and flavouring process takes 30 minutes, followed by a 15-minute waiting period and 15 minutes for pasteurization. After a 10-minute transfer to storage, a 40-minute quality check is performed before filling, which takes 390 minutes. The products then undergo a 480-minute incubation period before being stored for seven days for quality approval. Once approved, the products are distributed based on demand.

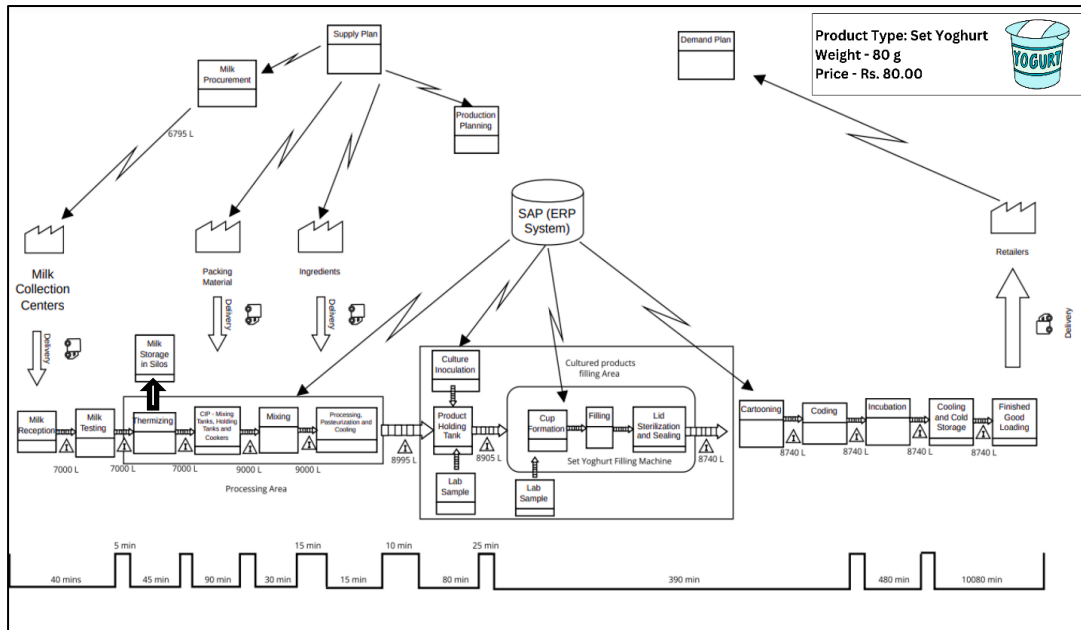


Figure 3: Value stream map of the set yoghurt production

3.2 Identification of Activities

Activities within production can be understood as the specific actions or steps carried out at each stage of the process. Value-added activities are those that directly enhance the final product from the customer’s perspective. Meanwhile, essential non-value-added activities do not add direct value to the product but are necessary to facilitate the process. Non-value-added activities contribute no value and represent inefficiencies. (Karida & Treptow, 2023) The table categorizes the activities observed in this production line. Non-value-adding activities are recognized and should be prioritized for elimination.

The production process of the set yoghurt production encompasses a series of value-creating activities crucial for achieving high product quality, consistency, and readiness for the market. These activities include thermization, mixing and flavoring, deaeration, homogenization, pasteurization and cooling, culture inoculation, filling, labeling, and incubation. Each of these steps directly contributes to the value of the final cultured milk product. Essential non-value-creating activities include Clean-in-Place (CIP) procedures to uphold hygiene standards, lab sample testing for quality assurance, ingredient weighing, and the transferring of ingredients using equipment such as a reach truck. Additionally, tasks like updating formulations in the computer, loading packaging materials into machines, and pallet transportation to storage support production continuity. Conversely, non-value-creating activities deplete resources without enhancing product value and should be minimized for greater process efficiency. Examples include the disposal of product mix and packaging materials, downtime during production, unnecessary extended production time, batch holds for prolonged periods, and garbage disposal. Among these activities, the disposal of the product mix emerged as a significant area of concern. Reducing or optimizing these non-value-creating activities is essential for boosting overall production efficiency and reducing waste. (Table 2)

Table 2: Classification of Activities in the set yoghurt production process

Value-Creating Activities	Essential Non-Value-Creating Activities	Non-Value-Creating Activities
Thermization	Clean-in-Place (CIP)	Disposal of the product mix
Mixing, flavoring, and standardization	Ingredient weighing	Disposal of packaging material

Deaeration	Lab sample testing	Downtime during production
Homogenization	Updating formulation in the computer (Fat and SNF values)	Added production time
Pasteurization and cooling	Transferring ingredients using the reach truck	
Culture inoculation	Packaging and labelling material loading into the machine	
Filling	Pallets transporting into storage	
Labelling and packaging	Cold storage	
Incubation	Batch hold for 7 days	
	Garbage disposal	

3.3 Product Mix Wastage

By analyzing the value stream map of the production line, the product mix is identified as one of the main wastages which is faced by the plant. In accordance with the Standard Operating Procedure (SOP) manuals, a standardized scrap factor is implemented for each product type to account for unavoidable wastage inherent in the production process. The scrap factor is expressed as a percentage of the total production volume in kilograms, reflecting the expected material loss due to processing steps. Specifically, the scrap factor for set yoghurt is 0.96% for the product mix. It is around 90 liters per set yoghurt batch. Figure 8 shows product mix wastage over a 12-month period, totaling 34,394 kg across all batches. On average, each batch incurred a wastage of 148.25 kg. (Figure 4)

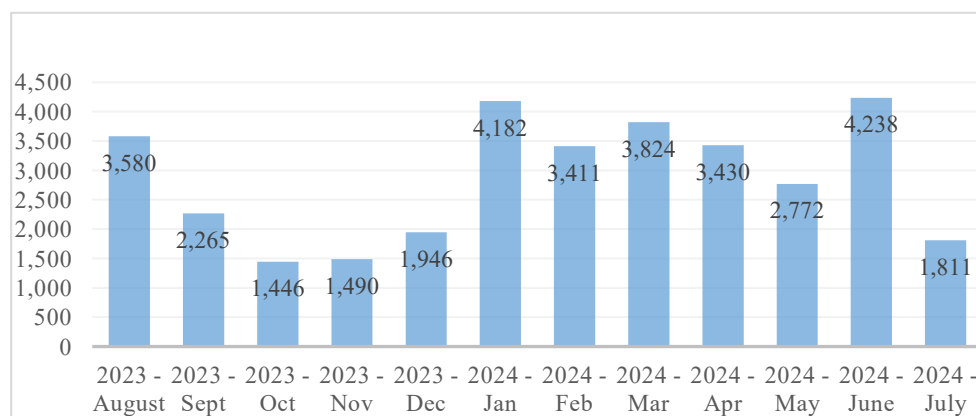


Figure 4: Product mix wastage in kilograms

3.4 Production Flow: An Account of Losses

3.4.1 During Batch Startup

During batch startup, milk is combined with major and minor ingredients, mixed, heat-treated, and transferred to storage tanks. Product mix wastage occurs when the product mix contacts residual water in transfer lines following the Clean-in-Place (CIP) process. This water-product mixture is drained at several points to ensure the desired consistency, resulting in significant losses. Key waste hotspots include Point A at the flow plate, where approximately 5 liters are drained; Point D at the balance tank, with around 90 liters lost due to the line's length; and Point E at the filling machine nozzles, where an average of 65 liters is wasted. These losses are influenced by operator judgment during draining, emphasizing the critical role of expertise in minimizing waste and maintaining product quality. (Figure 5)

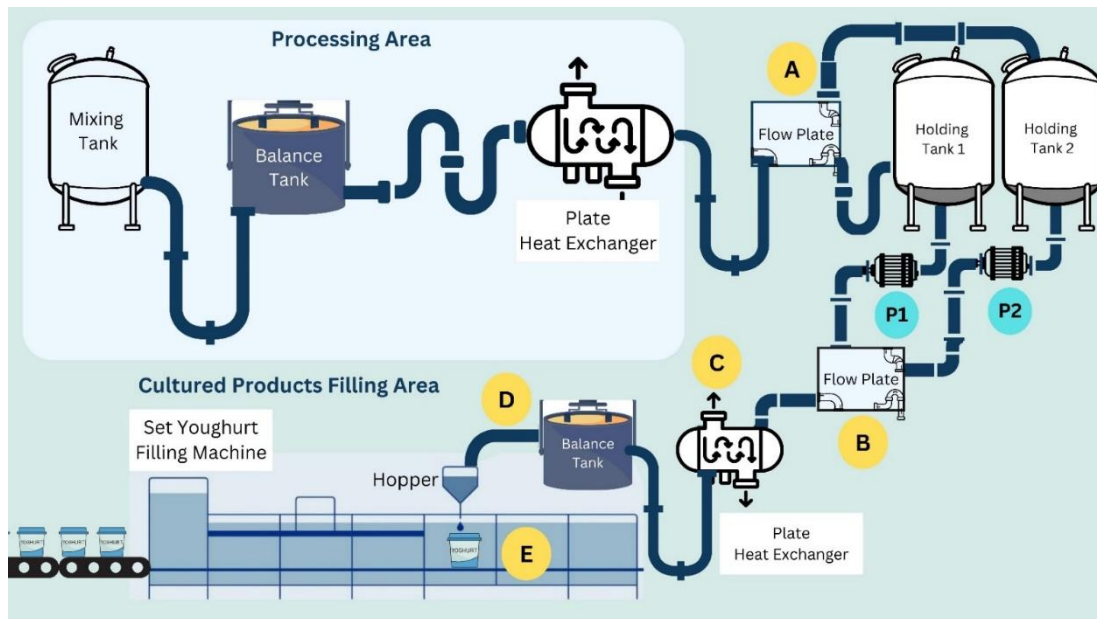


Figure 5: The Loss Map of the Set Yoghurt Manufacturing Process

3.4.2 During Batch Changeover

Scenario 1: Similar Product Line

When transitioning to a similar product, the mix is transferred to a new holding tank (Holding Tank 2). Water in the transfer lines is drained at Point A, resulting in 5 liters of product mix wastage. After sampling and adding culture, the filling process can be started. Since the batch type is the same, no further flushing is required, with Point A being the only waste hotspot.

Scenario 2: Different Product Line

For different product batches, a new holding tank is used. Initial line flushing at Point A causes 5 liters of waste. Additionally, the balance tank at Point C and the filling machine nozzles at Point E have been identified as critical waste hotspots, where residual product must be removed to clear the lines for the next batch. This process involves draining portions of both mixes, leading to an average product mix loss of 100 liters.

Table 3: Summary of Product Mix Wastage at a batch changeover

Scenario	Waste Hotspot	Waste Amount	Cause/s
When the Next Batch is a Similar Set Yoghurt Batch	Point A (Flow Plate)	5 L	Mix with water presence from CIP
When the Next Batch is a Different Set Yoghurt Batch	Point A (Flow Plate)	5 L	Mix with water presence from CIP
	Point D (Balance Tank) Point E (Filling Machine Nozzles)	100 L	Mix with residual product mix of the previous batch, operator handling variations

3.4.3 Final Stage of Production

After the product mix is pushed by pump (P1/P2) to its maximum capacity, the operators will fill the hopper and proceed with the filling process until the hopper is cleared. Once the filling is complete, lab tests are conducted on the final products. These last-filled products often exhibit issues such as lower fill levels, underweight, or substandard texture. Testing continues until a product meets the required standards. All products produced after this point are considered wastage, resulting in approximately 10 liters of product mix loss. Despite the pump operating at maximum capacity, a portion of the product mix remains in the lines and cannot be recovered. This unrecoverable product is considered wastage. In each production cycle, the line loss typically averages between 70 to 100 liters.

The waste hotspots for product mix at the end of the production, along with their corresponding wastage amounts and potential causes, can be summarized as follows:

Table 4: Summary of Product Mix Wastage at the end of the production

Waste Hotspot	Waste Amount	Cause/s
At the end of the production	10 L	Last-filled products which exhibit issues such as lower fill levels, underweight, or substandard texture
At the end of the production	100 L	Product mix remaining in the lines, known as line loss, is considered unrecoverable

3.5 Losses Due to Machine Faults

Machine faults significantly contribute to product mix wastage, alongside waste hotspots in the processing steps. An analysis of 12 months of data and discussions with operators identified the most frequent faults and their associated wastage levels. Among these, the low temperature issue causes the highest wastage, with 70 liters lost per occurrence due to extended downtime exceeding 30 minutes, leading to temperatures dropping below the required 42°C standard between the plate heat exchanger (Point C) and the filling machine (Point E). Lid eye mark deviation, where misaligned lid markings render products non-compliant, and cup blast, caused by cups getting stuck in the machine, each result in 30 liters of wastage. Minor faults such as red label joint defects, cup bottom issues, and weak sealing contribute an additional 5 liters of wastage per incident. These faults collectively represent a significant source of inefficiency in the production process.

Table 5: The summary of machine-related production mix losses

Machine Fault	Amount of Product Mix Wastage
Red label joint	5L
Lid eye mark deviation	30L
Low temperate	70L
Cup blast	30L
Cup bottom issues	5L
Weak sealing	5L

3.6 Losses Due to Human Errors

Human factors also contribute to product mix wastage alongside process and machine-related losses. Operators play a key role during the draining process, relying on their experience to determine when the product mix reaches the correct texture and ensuring water residue is removed. Out of caution, they may occasionally drain correctly textured product mix to avoid lab test failures. This process also involves connecting lines at multiple flow plates, which must be carried out with utmost precision. Even a single error can result in the wastage of an entire batch. During tea breaks, operators often close the valve at the holding tank, allowing the hopper to fill with the remaining product mix and continuing production until the mix in the lines is used. They clear the hopper and the line between the plate heat exchanger and the filling machine because, during the break, the product mix experiences a temperature

drop below the required 42°C standard. When production resumes, approximately 70 liters of product mix must be drained due to the temperature issue. Despite efforts to clear the lines beforehand, additional wastage occurs at the end of production due to low-volume filling and underweight issues. These actions collectively result in product mix losses attributed to human factors.

3.7 Minimizing Waste and Improving Efficiency

3.7.1 Process Improvements and Practice Changes

Dairy processing waste can be broadly categorized into physical waste (including product and packaging material loss), energy waste, and water waste. Identifying waste hotspots is fundamental for enhancing efficiency and sustainability (Ramirez et al., 2006). This research aligns with these findings, revealing that product mix wastage represent significant physical waste within the production plant. Outdated equipment, suboptimal process control, and human factors as common sources of inefficiency (Kalla et al., 2019). Consistent with these insights, this research also identified suboptimal processes, machine malfunctions, and human errors as primary root causes of product mix wastage.

Following the development of a loss map and a thorough analysis of wastage points, a focus group discussion was conducted involving a cross-functional team from manufacturing, food safety and quality, finance, and engineering. These discussions, along with input from operators and employees directly involved in daily production processes, highlighted the potential benefits of providing operators with a Brix meter. Brix indicates the number of dissolved solids in a liquid, measured via its specific gravity (SG). This measurement is particularly relevant in the food and beverage industry, where it is used to assess product quality. Sample-based Brix measurement is commonly applied in commercial settings, such as wineries, to monitor and maintain product consistency (Jaywant, Singh, & Arif, 2022). This tool would allow operators to pinpoint the exact moment when the actual product begins to drain, thereby reducing wastage at key points in the process, specifically at points A, D, and E (Figure 12).

To ensure operators can effectively utilize the Brix meter, it is recommended to organize targeted training sessions. These sessions should focus on interpreting Brix values and recognizing the correct product texture, enabling operators to make informed decisions during production.

Another suggestion raised during the discussion focuses on revising the batch changeover procedure. Standardization is a crucial tool for driving continuous improvement in manufacturing operations. By capturing and documenting the best current practices, standardized work provides a foundational baseline for ongoing enhancement. This iterative process not only minimizes process variability but also enhances product and process quality, ensuring sustained operational excellence (Míkva et al., 2016). In a batch changeover, instead of halting production and draining the system after the final filling of the hopper, it was proposed to continue production. The products produced after this final hopper filling would be isolated in a separate area for laboratory testing, starting with the last produced product and moving backward, to determine the point where no defective products are present. This approach minimizes product mix wastage typically discarded during changeovers, as production continues using the mix remaining in the lines.

Another suggestion is to revise the operator practice during tea breaks. Currently, when operators go for a break, they close the valve at the holding tube and fill the hopper with the product mix remaining in the line from the holding tank. They continue production until the hopper is emptied, treating it as the end of the batch. However, this leads to wastages at the end including low volume fills, underweight products, and texture inconsistencies, increasing overall batch waste. The proposed improvement is to alternate tea breaks between the two operators managing the filling process. Instead of both operators taking a break at the same time, one can go for a break while the other continues managing the machine. Once the first operator returns, the second can take their break. This approach ensures continuous machine operation and reduces the wastage associated with product mix and packaging materials that occurs during stoppages.

The use of visual management (VM) can significantly enhance communication among participants in the work process. By employing a range of visual tools and techniques, companies can ensure that processes are carried out smoothly and efficiently. Tailoring visual management methods to suit specific operational needs helps streamline workflows, reduce misunderstandings, and improve overall process transparency, thereby fostering a more cohesive and productive work environment (Małysa & Furman, 2021). The use of color-coded flow plates and indicator boards can significantly help in highlighting high-risk areas that require focused attention from operators. This visual management tool reduces the likelihood of human errors and minimizes mistakes in line connections, contributing to smoother operations.

3.7.2 Machine Improvements

The filling machine itself plays a significant role in contributing to product mix as outlined in previous sections, certain unavoidable situations, such as machine startup and shutdown, red label joints, and batch changeovers, lead to product mix wastage that cannot be easily recovered or reduced. Other issues, such as cup blasts, weak sealing, reel melting, and lid eye mark deviations, result in unplanned machine downtime and further contribute to waste in terms of product mix, packaging materials, and time. Addressing these faults is critical for improving overall equipment efficiency.

Preventive maintenance (PM) is a proactive strategy in asset management that involves scheduled activities such as inspections, cleaning, lubrication, adjustments, repairs, and part replacements. Its primary objective is to prevent unexpected equipment failures and extend the operational lifespan of assets. Calibration, on the other hand, involves comparing an instrument's measurements against a traceable reference standard of known accuracy to ensure precision. Both preventive maintenance and calibration play crucial roles in maintaining asset reliability, ensuring that equipment operates at optimal performance and accuracy (Genest, 2024). This research found that implementing scheduled preventive maintenance and calibration for each machine is essential for minimizing machine errors.

Autonomous maintenance is a tool which stems from the eight foundations of the lean philosophy tool of the Total Productive Maintenance structure (TPM). Its aim is to eliminate all the forms of time expenditure associated to stoppages in the productive system due to machine breakdowns, which invariably produce a direct impact on process performance (Wakjira, Workneh & Ananth, 2014) Autonomous Maintenance is, therefore, essential to the implementation of TPM; it enables greater production throughput and includes the support of the company's employees (Kiran, 2016). To implement these targets, greater responsibility must be given to the operators: these must be made fully aware of their role in ensuring both the quality of the product, as well as the efficient running of machines to achieve significant improvement in equipment performance (Womack, James & Jones, 2003)

The manufacturing facility has implemented seven key steps of autonomous maintenance. These steps aim to gradually strengthen the operators' ability to maintain and troubleshoot equipment, ensuring long-term reliability and minimizing waste.

The seven steps of autonomous maintenance are as follows:

- Step 0: Preparation
- Step 1: Cleaning to Find Problems
- Step 2: Address Sources of Problems (contamination/hard-to-reach areas)
- Step 3: Establish Cleaning, Inspection, and Lubrication Standards (CIL)
- Step 4: Equipment Component/Process Inspection (Define the zero-loss state)
- Step 5: Address System Problems
- Step 6: Address Product Quality Problems
- Step 7: Practice Continuous Improvement

The set yoghurt filling machine is currently at Step 3 of the autonomous maintenance process. Following focused group discussions, the decision was made to advance to Step 4: Equipment

Component/Process Inspection, with the objective of defining the “zero loss state.” This initiative aims to significantly reduce wastage in the form of product mix.

In Step 4 of autonomous maintenance, implementation can be started by identifying the various types of losses associated with the machine. This analysis encompasses several categories, including minor stops, breakdowns, process failures, safety losses, quality losses, material losses, and energy losses. Once these losses are identified, they are prioritized to develop a machine transformation matrix and conduct a work point analysis. This process helps pinpoint the most impactful areas of the machine that contribute to these losses. Following this analysis, necessary corrective actions will be taken to address the identified faults and minimize the associated losses.

4. Conclusion and Recommendations

This study provides a comprehensive analysis of the production process for set yoghurt within a cultured product manufacturing plant. The primary objective of investigating the value chain of set yoghurt production line and developing a value stream map has yielded significant findings that address key areas of waste hotspots, inefficiencies, and opportunities for improvement within the production process. The research identified product mix wastage as the major type of material waste. Waste hotspots were most pronounced during batch startups, changeovers, and at the end of production, where human errors and machine faults were found to exacerbate the losses. In addition, the study revealed that machine malfunctions and operator errors are major contributors to inefficiency. The findings of this study are consistent with existing literature on inefficiencies in dairy production, highlighting the importance of addressing process, technical and human factors to reduce waste and enhance overall production performance. To overcome the identified inefficiencies, several strategies are recommended. These include providing operators with a brix meter and proper training in its usage, standardizing best practices through detailed Standard Operating Procedures (SOPs), and implementing visual management systems in the production area to minimize human errors. Additionally, establishing preventive maintenance and autonomous maintenance routines will help maintain machine efficiency. The implementation of Autonomous Maintenance Step 4 in the set yoghurt filling machine, with a focus on addressing major losses. These combined strategies will significantly minimize waste, improve efficiency, and contribute to cost savings and sustainability in the production of cultured dairy products.

Drawing from the key insights of this study, it is recommended that the proposed solutions be implemented in order of ease and feasibility. Initial priorities should focus on internal initiatives that can be facilitated with existing resources and collaborative efforts. Providing brix meters along with comprehensive training for operators, revising practices, and standardizing procedures through enhanced SOPs, as well as implementing visual management systems to mitigate human errors, can be prioritized as these can be accomplished with the support of the liquid manufacturing, food safety and quality, and continuous improvement departments.

From a machine-centric perspective, initiating the implementation of Autonomous Maintenance (AM) Step 4 for the three filling machines is advised. This process, which unfolds over an extended period, can be rolled out progressively in a step-by-step manner. The successful execution of this initiative will require close collaboration between the manufacturing, food safety and quality, engineering, and continuous improvement teams.

References

- Amani, P., Lindblom, I., Sundstrom, B. and Ostergren, K. (2015) 'Green-lean synergy: Root-cause analysis in food waste prevention', *Food Waste Management*, 32(2), pp. 45–50.
- Auldish, M.J., et al. (2010) 'Recycling of cleaning solutions in dairy processing plants', *Journal of Dairy Science*, 93(6), pp. 2554–2560.
- Aung, M.M. and Chang, Y.S. (2018) 'Temperature management for the quality assurance of a perishable food supply chain', *Food Control*, 40, pp. 198–207.
- Bait, S., Di Pietro, A. and Schiraldi, M.M. (2019) 'Waste reduction in production processes through simulation and value stream mapping', *International Journal of Production Research*, 57(12), pp. 1827–1845.
- Chandrapala, J., et al. (2017) 'The efficiency of membrane filtration in dairy processing: A review', *International Dairy Journal*, 69, pp. 25–37.
- D'Espina Karida, S.T. (2023) 'Waste analysis on a production line: A case study', *Lund University Research Reports*, 12, pp. 1–15.
- Dinis-Carvalho, J., Guimarães, L., Sousa, R.M. and Leão, C.P. (2019) 'Waste identification diagram and value stream mapping: A comparative analysis', *International Journal of Lean Six Sigma*, 10(3), pp. 767–783.
- Doggett, A.M. (2005) 'Root cause analysis: A framework for tool selection', *Quality Management Journal*, 12(4), pp. 34–45.
- Enes, E. and Kipoz, S. (2019) 'The role of fabric usage for minimization of cut-and-sew waste within the apparel production line: Case of a summer dress', *Clothing and Textiles Research Journal*, 37(1), pp. 27–40.
- Kalla, S., et al. (2019) 'Energy efficiency improvements in the dairy industry', *Journal of Cleaner Production*, 211, pp. 268–277.
- Kholil, M. and Haekal, J. (2021) 'Lean Six Sigma integration to reduce waste in tablet coating production', *Procedia Manufacturing*, 53, pp. 123–132.
- Nihlah, Z. and Immawan, T. (2018) 'Lean manufacturing: Waste reduction using value stream mapping', *Journal of Productivity and Efficiency*, 45(3), pp. 78–89.
- Ohno, T. (1988) *Toyota Production System: Beyond Large-Scale Production*. New York: Productivity Press.
- Pereira, C.R., et al. (2019) 'Employee training and its impact on productivity and efficiency in the food processing industry', *Food Quality and Preference*, 73, pp. 54–64.
- Ramirez, C.A., et al. (2006) 'Energy efficiency improvement and cost-saving opportunities for the dairy processing industry', *Energy*, 31(13), pp. 1970–1983.
- Salas-Velasco, M. (2018) 'Resource misallocation and production inefficiency: Estimating cross-country differences in macroeconomic performance', *Journal of Economic Studies*, 45(6), pp. 1272–1287.
- Sharma, M., et al. (2020) 'Lean manufacturing in dairy processing: A review', *Journal of Food Engineering*, 265, 109686.
- Singh, B., et al. (2011) 'Application of value stream mapping in the dairy processing industry', *International Journal of Food Science and Technology*, 46(5), pp. 1013–1021.
- Spiegel, M. van der, et al. (2013) 'Advanced process control in dairy manufacturing', *Trends in Food Science and Technology*, 33(2), pp. 77–84.
- Thomassen, M.A., et al. (2008) 'Environmental impact and energy consumption of milk production: A review', *Agriculture, Ecosystems and Environment*, 126(1–2), pp. 45–56.
- Tomei, J., et al. (2017) 'Human factors in the dairy processing industry: Impacts on efficiency and product quality', *Journal of Dairy Research*, 84(3), pp. 341–349.
- Verdouw, C.N., et al. (2016) 'Internet of Things in the food supply chain: From lab to field', *Computers and Electronics in Agriculture*, 127, pp. 10–18.
- Wesanaa, J., Gellynck, X., Dora, M.K., Pearce, D. and De Steur, H. (2019) 'Measuring food and nutritional losses through value stream mapping along the dairy value chain in Uganda', *Resources, Conservation and Recycling*, 13, pp. 82–95.
- Womack, J.P. and Jones, D.T. (2010) *Lean Thinking: Banish Waste and Create Wealth in Your Corporation*. New York: Free Press.

- Zakaria, N.H., Mohamed, N.M.Z.N., Rahid, M.F.F.A. and Rose, A.N.M. (2017) 'Lean manufacturing implementation in reducing waste for electronic assembly line', *Journal of Industrial Engineering*, 23(2), pp. 67–79.
- Zhi, W. and Sun, L. (2018) 'Waste identification diagrams: A comparative analysis with value stream mapping', *Procedia Manufacturing*, 21, pp. 24–33.



ICRES26_059

POLYSACCHARIDE-BASED BIODEGRADABLE FILMS FOR RESOURCE-EFFICIENT PACKAGING: STRUCTURAL ENGINEERING, PERFORMANCE OPTIMIZATION AND SUSTAINABILITY PERSPECTIVES**A.S.S. Jahan^{*}, A.M.R. Ahamed***Department of Biological Sciences, Faculty of Applied Sciences, South Eastern University, Sri Lanka***Corresponding E-mail: samroothsaleem@gmail.com, TP: +94768333244*

Abstract: Petroleum-based plastic waste, especially short-lifetime packaging, has become an overwhelming source of environmental degradation and resource inefficiency. Polymers made from petroleum-based materials like polyethylene and polypropylene last for decades and contribute to landfills, ocean pollution, and greenhouse gases. In response to this crisis, this review examines the need for biodegradable, renewable alternatives based on polysaccharides from plants (starch, cellulose), sea creatures (alginate, chitosan) and microorganisms (pullulan). This study reviews literature on the polysaccharide film products of the past 25 years to evaluate structure-property relationships, physical-chemical properties, modification strategies, uses and life-cycle sustainability issues. Mechanical properties of polysaccharide-based films vary greatly depending upon crystallinity, hydrogen bonding, molecular weight and degree of substitution; mechanical properties range from 5-20 MPa for plasticized starch films to 45-90 MPa for cellulose-based films. However, all polysaccharide-based films exhibit high water vapor permeability due to their high levels of inherent hydrophilicity; this may cause performance to degrade at humidity > 60-70 % RH. Several methods, such as controlled plasticization, green cross-linking (citric acid and Ca²⁺ networks) and nanocomposites containing cellulose nanocrystals, have been used to improve tensile strength of polysaccharide-based films by up to 100 % and reduce water vapor transmission rates through these films by up to 60 %. In addition, life-cycle analyses indicate a reduction in the use of fossil fuels and greenhouse gases compared to conventional petroleum-based plastics, especially if the polysaccharide films are produced from waste-based feedstock. There are still many barriers to the widespread adoption of polysaccharide films, including moisture resistance, scale-up of manufacturing processes, standardizing test protocols and long-term durability. In conclusion, polysaccharide-based films are a viable path forward toward a bio circular economy, if advances are made in both polysaccharide-based material development and comprehensive life-cycle assessments to support large-scale, resource efficient production.

Keywords: Biodegradable; Circular economy; Nanocomposites; Polysaccharide films

1. Introduction

Plastic waste is a global environmental problem, primarily due to the long-lasting nature of plastics and how they accumulate in the world's ecosystems. According to PlasticsEurope (2023), plastic production in 2022 was at 400 million metric tons, with packaging accounting for about 36-40% of all plastic used. Since the 1950s over 8.3 billion metric tons of plastic have been produced, and although less than 9% of the plastic produced has been recycled, the majority of it has either ended up in landfills or has been discharged into the environment (Geyer et al., 2017). It is believed that inadequately managed waste systems allow for about 8-12 million metric tons of plastic to enter marine environments each year (Jambeck et al., 2015). Chemical breakdown of macro-plastic waste products by means of exposure to sunlight (UV light) and physical fragmentation, also degrades larger plastic debris into smaller pieces called microplastics (less than 5mm). Microplastics have been found in almost every type of ecosystem (marine, freshwater, soil, atmospheric deposits, and human biological samples) and could potentially serve as vectors for contaminants as well as have the ability to negatively affect both ecological and human health (Thompson et al., 2004; Andrady, 2011; Wright et al., 2013; Leslie et al., 2022).

As a result of the long-lasting carbon-carbon backbone structure of conventional petroleum-based plastics (such as polyethylene (PE) and polypropylene (PP)) there is very little degradation of these types of plastics by microbes. Therefore, developing biodegradable and bio-based plastic alternatives based on renewable biomass feedstocks has become a top research priority in terms of reducing the amount of plastic waste generated and increasing the sustainability of material cycles (European Commission, 2018).

Biopolymers, specifically those made from plant-derived polysaccharides, are considered to be among the most common and structurally varied natural macromolecules available for conversion into commercially viable polymers. Worldwide, cellulose is synthesized at a rate greater than 10^{11} tonnes per year and represents the greatest abundance of biopolymer on earth (Klemm et al., 2005). Polysaccharides are composed of sugar units bonded together via glycosidic linkages and may form linear or branched configurations based on the biological source of the polymer (Tharanathan, 2003). Hydrogen-bonded interactions facilitated by the many functional groups present on polysaccharides (hydroxyl, amino, carboxyl, etc.) enable extensive structural modification of polysaccharides that can significantly increase their mechanical and barrier properties (Rhim et al., 2013).

Films prepared from polysaccharide-based polymers have attracted considerable interest in recent years as possible materials for developing sustainable packaging applications. Biopolymer films have shown great promise in terms of their mechanical properties, exhibiting tensile strength values as high as 100 MPa and as low as 3 MPa, depending upon the formulation and processing conditions employed. These tensile strengths are comparable to those exhibited by certain commercial packaging materials, including low-density polyethylene (LDPE) (8-25 MPa) (Avérous, 2004; Siracusa et al., 2008). Unfortunately, biopolymer films are typically highly hydrophilic, leading to relatively high water vapor transmission rates when exposed to humid conditions (Bourtoom, 2008). To overcome the limitations inherent in polysaccharide films, researchers have employed a variety of methods to modify the mechanical properties and barrier performance of biopolymer films, including cross-linking, plasticization, and incorporation of nanofillers (nanocomposites). Although numerous approaches have been developed to enhance the performance of biopolymer films, a number of barriers still exist, including issues related to moisture sensitivity, the wide range of test protocols employed, the lack of an adequate understanding of the extent of biodegradation following chemical modification of polysaccharides, and challenges related to the large-scale production of polysaccharide-based films.

Given the need for a comprehensive and critical assessment of polysaccharide-based films as a sustainable alternative to conventional plastic packaging materials, this review will focus on examining the chemical structures and functional properties of the most common polysaccharides, comparing the physicochemical properties of polysaccharide-based films to those of traditional plastics, evaluating the effectiveness of the current modification strategies employed to enhance the performance of

polysaccharide-based films, and identifying areas of needed research to advance the large-scale industrial use of polysaccharide-based films.

2. Methodology

This review was carried out in accordance with the guidelines of the Preferred Reporting Items of Systematic Reviews and Meta-Analyses (PRISMA) 2020 which offer a clear and methodological system of identifying, filtering and choosing the appropriate literature. Though PRISMA was initially designed to be used in clinical research, it is also being used in materials science and engineering reviews to enhance the methodological transparency and reproducibility, especially when systematizing experimental studies of physicochemical, mechanical, and barrier properties of biomaterials like polysaccharide-based films. The exhaustive literature search involved the use of Scopus, Web of Science, ScienceDirect and Google Scholar with a mix of key words such as polysaccharide-based films, biodegradable packaging materials, biopolymer films, cellulose films, chitosan films, starch-based films, mechanical properties, barrier properties and sustainable packaging. The search was restricted to publications published in the 2000-2025 to identify the latest technological innovations in the field of biodegradable polymers research, especially the advancement of film processing, nanocomposite reinforcement (e.g., nanocellulose), and chemical modification of polysaccharides, which have become predominant within the last 20 years.

The choice of the study was in line with the PRISMA phases of identification and selection, screening and inclusion. Eighty-two articles were first identified. The articles that survived title and abstract screening to eliminate duplicates and irrelevant articles were then subjected to full-text review to check the eligibility in terms of having clear experimental methodologies and quantifiable physicochemical data on polysaccharide-based films. Eventually, the review involved 68 studies. Research works were considered to be included in case they examined polysaccharide-based biodegradable films used in packaging or reported mechanical, thermal, or barrier properties and detailed experimental procedures. They had filtered out 14 articles they deemed insufficiently detailed in their methodology, such as lack of information regarding film preparation techniques, tensile test conditions, barrier testing conditions, or incomplete characterization data.

The methodological quality of the included studies was determined by the completeness of the reporting in terms of the use of experimental procedures, the use of standardized methods of mechanical testing, the specification of the conditions of environmental tests, and the reporting of results of replicates or statistical analysis. Research papers that were deficient of methodological transparency were eliminated so that the reliability and comparability of the reviewed data would be ensured.

3. Structural Classification and Molecular Determinants of film performance

Plant derived polysaccharides include starch, cellulose, and nanocellulose, and have been explored as biodegradable components of film systems. The mechanical properties and environmental responses of these materials are determined by their macromolecular architectures, crystallinity, hydrogen bonding densities, degrees of substitution, and molecular weight distributions. In addition to the inherent material properties, the structural properties of starch and cellulose may be altered by various processing methods such as plasticization, chemical modification, and mechanical deformation

3.1 Plant-Derived Polysaccharides

Starch is a widely available polysaccharide that has been studied extensively as a potential film forming material due to its thermoplastic behaviour when plasticized. Structurally, starch is composed of amylose (α -1,4-linked D-glucose) and amylopectin (α -1,4 and α -1,6 linkages). Amylose is responsible for the majority of the structural cohesion that develops during film formation due to the ability of its linear chains to organize themselves and crystallize through hydrogen bonding. Studies conducted by Pelissari et al. (2017) demonstrate that an increase in amylose content results in a significant improvement in tensile strength and reduction in solubility of starch films resulting from enhanced molecular organization and development of crystalline domains. Similar research by Ballesteros-Mártinez et al. (2020) reported tensile strengths for plasticized starch films, which were found to be

significantly affected by the concentration of glycerol used as a plasticizer and humidity of the environment. Increased levels of plasticizers interfere with hydrogen bonding networks causing reductions in tensile strength but increases in flexibility.

The balance of crystalline and amorphous regions also plays a key role in determining how well a starch-based film will perform under different conditions. Priyadarshi and Rhim (2020) noted that increased crystallinity provides improved tensile strength and rigidity, however, this comes at the cost of reduced elongation due to restricted chain mobility. Research has confirmed that both the composition of starch and the molecular weight distribution of starch affects physical properties, with higher amylose content typically providing improved mechanical properties (Domene-López et al., 2019; Zhang et al., 2024). However, starch films inherently provide high levels of water vapor permeability, due to the hydrophilic nature of hydroxyl groups allowing for the passage of moisture. Both the type and amount of plasticizer used in starch film processing influences moisture sensitivity and barrier characteristics (Tarique et al., 2021). Therefore, the performance of starch films is heavily dependent upon the molecular structure and plasticization method utilized in their production, therefore, there is a need to tailor structural aspects of starch films for specific uses in packaging applications

3.2 Cellulose and Nanocellulose

Cellulose is made up of repeating units of D-glucose molecules that are β -1,4 linked, which assemble into highly ordered crystalline microfibrils held together by strong intra- and inter-molecular hydrogen bonding and electrostatic forces (Jarvis, 2022; Beckham et al., 2011). The rigid packing of cellulose confers it high stiffness, low solubility, and resistance to enzymatic degradation, primarily due to the limited mobility of chains in crystalline regions compared to most other polysaccharides. Chemical modifications, including etherification to create hydroxypropyl methyl cellulose (HPMC) and carboxymethyl cellulose (CMC), substitute some of the hydroxyl groups of cellulose and disrupt the native hydrogen bonding networks of cellulose, resulting in lower crystallinity and higher solubility in water and improved processability (McMullen et al., 2022). The degree and types of substitution influence the viscosity and water affinity of solutions containing derivatives of cellulose, enabling the use of these derivatives as film formers and as delivery vehicles for bioactive agents (Wang et al., 2023). Addition of 2-4 wt.% CMC or HPMC to alginate matrices resulted in tensile strengths that were significantly greater than those without added cellulose derivatives, with CMC exhibiting decreased water solubility and HPMC exhibiting increased water solubility, likely due to the difference in hydrophilicity (Abdul Hadi et al., 2022).

Tensile strengths of regenerated cellulose films range from 90-155 MPa and are influenced by the extent of alignment of polymer chains and restriction of mobility of non-crystalline regions, as opposed to crystallinity alone (Wang et al., 2024). Moisture acts as a plasticizer to reduce tensile strength and Young's modulus, while increasing elongation and water vapor permeability (Cazon et al., 2020). Reinforcement of nanocellulose further improves stress transfer through hydrogen bonded networks (Gupta et al., 2022; Zhang et al., 2024), and failure mechanisms involve rupture of glycosidic bonds (Beckham et al., 2011).

3.3 Marine derived Polysaccharides

Although numerous types of marine-derived polysaccharides exist, this review will focus on two of the most studied: chitosan and alginate. Chitosan has been extensively studied as a potential antimicrobial agent and biodegradable material used for packaging.

Chitosan is the result of partial deacetylation of chitin, the second-most abundant natural polymer after cellulose (Kumar et al., 2009). It is a cationic polysaccharide that contains reactive amino (-NH₂) groups along its backbone. These reactive amino groups enable it to form electrostatic interactions and have inherent antimicrobial activity. The mechanical and functional properties of chitosan films depend on the molecular weight, degree of deacetylation (DD), and amount of plasticizer added to the films (Bonilla et al., 2018). Glycerol is commonly used as a plasticizer for chitosan films (Bonilla et al., 2018; Jahan and Haroon, 2025). As a general rule, tensile strength values for glycerol-plasticized

chitosan films range from 28-46 MPa and provide adequate mechanical strength for use in flexible packaging applications (Bonilla et al., 2018). Molecular weight affects the mechanical properties of the film. At higher molecular weights, the number of intermolecular hydrogen bonds increases and the chains become more entangled, thus increasing the tensile strength of the film, but decreasing its elongation and flexibility (Ahmed et al., 2016). In addition to modifying the mechanical properties of the film, chitosan incorporated into polylactic acid (PLA) matrices creates less rigid and less stretchy materials than pure PLA, while providing a significant increase in antimicrobial activity (Bonilla et al., 2020).

The mechanism of action of chitosan in exerting antimicrobial activity is generally believed to involve the protonation of the amino groups present on the molecule at low pH, producing $-NH_3^+$ moieties that interact electrostatically with negatively charged components of bacterial membranes, creating a pathway for increased membrane permeability and subsequent cell lysis (Muñoz-Bonilla and Fernández-García, 2013; Kong et al., 2015). Furthermore, blended systems utilizing chitosan have demonstrated enhanced performance over single component systems. For example, films comprising of gelatine-chitosan composites that were activated with plant extracts exhibited both improved antimicrobial and antioxidant stabilities and acceptable mechanical properties (Bonilla et al., 2018). Studies assessing the compost ability of chitosan films indicate that these films undergo complete degradation within controlled composting environments, providing evidence for their potential environmental compatibility (Bonilla et al., 2020). Therefore, chitosan films provide a unique combination of mechanical strength, antimicrobial functionality and biodegradability, where the performance of the films are dictated by molecular properties and interactions with the surrounding matrix, providing a basis for consideration as potential active biodegradable packaging materials.

3.4 Alginate

It is a linear block copolymer composed of beta-D-mannuronic (M) and alpha-L-guluronic (G) acid residues arranged in homopolymer (poly-M, poly-G) and heteropolymer (poly-MG) sequences (Draget et al., 2005). Alginate's ability to undergo gelation is determined by the sequence of mannuronic and guluronic acid residues in the polymer and by the presence of divalent metal ions such as calcium, magnesium and strontium. In particular, calcium ions tend to bind to guluronic rich regions of the polymer forming "egg box" type structures, which create a three-dimensional network of polymer chains that provides mechanical strength (Draget et al., 2005). Alginates with higher guluronic contents produce stronger and more elastic gels than those with lower guluronic contents because of the greater degree of crosslinking that occurs (Draget et al., 1994). Conversely, alginates that contain a higher proportion of manuronic acid tend to produce softer gels (Draget et al., 1994). Crosslinking alginate films with calcium ions results in a significant increase in tensile strength and decrease in solubility compared to uncross linked films (Rhim, 2014).

However, if too many crosslinks are created in the alginate network, then the resulting gel can become brittle and lose elasticity. The structural characteristics of the alginate network can be further modified by adding oligoguluronate or chitosan oligomer components to the system. Oligoguluronates can alter the rate at which the alginate network forms, while chitosan oligomers can modify the number of junctions that occur within the network (Jørgensen et al., 2007; Kopplin et al., 2021). Therefore, the physical properties of alginate-based materials are determined by the molar ratio of guluronic to manuronic acids, the concentration of calcium ions available for crosslinking, and the density of crosslinks within the network.

3.5 Microbial Polysaccharides

Pullulan is a polysaccharide produced by microorganisms, specifically *Aureobasidium pullulans*, and consists of repeating units of maltotriose linked via alternating alpha-1,4 and alpha-1,6 glycosidic bonds (Leathers, 2003). Due to its soluble nature in water, pullulan is commonly isolated from fermentation broth using precipitation methods (Leathers, 2003). The production of pullulan is greatly influenced by the presence of sucrose in the growth medium, with optimal sucrose concentrations reported to range from 10-20 wt.% (Leathers et al., 1988). Nitrogen limitation in the culture medium also supports the

production of pullulan by promoting the accumulation of sucrose in the broth (Leathers et al., 1988). As the cultivation time of pullulan-producing microorganisms increases, the molecular weight of the polymer decreases as a result of enzymatic degradation (Leathers et al., 1988; Manitchotpisit et al., 2011). Low levels of extracellular alpha-amylase activity can lead to the cleavage of maltotetraose segments of the pullulan polymer chain, ultimately affecting the mechanical properties of pullulan-based films (Manitchotpisit et al., 2011; Prasongsuk et al., 2006). Under dry conditions, pullulan films demonstrate excellent oxygen barrier properties with permeability values that are similar to those of synthetic barrier polymers below 50% relative humidity (Leathers, 2016).

However, the oxygen barrier properties of pullulan films decline rapidly as the relative humidity exceeds 60% due to moisture-induced plasticization of the polymer film (Leathers, 2016). Beyond pullulan, A. pullulans also produce liamocins with specific anti-streptococcal activity, indicating the potential of this microorganism for multiple biotechnological applications (Price et al., 2013; Leathers et al., 2018). The successful development of pullulan-based products depends heavily on controlling the production process through manipulation of culture conditions, enzymatic activity, and cost efficiency.

Table 1: Structural determinants and their reported performance

Polymer / System	Key Structural Factor	Effect on Strength & Stiffness	References
Starch (native / high-amylose)	Amylose crystallinity; linear chain alignment	Higher amylose and ordered crystallites increase tensile strength (5–18 MPa typical) and modulus but reduce extensibility	Molavi et al., 2018; Rostamabadi et al., 2024
Cellulose & derivatives	β -1,4-linked crystalline domains	High crystallinity yields strong, stiff films (45–90 MPa); cellulose–starch blends retain strength under wet conditions	Rhim et al., 2015; Miyamoto et al., 2009; Dhalsamant et al., 2025
CNC-reinforced matrices	High-modulus nanofillers; percolated H-bond network	Well-dispersed CNC/nanoclays increase modulus and tensile strength (+30–60%) and improve gas barrier via tortuous path	Paula et al., 2018; Müller et al., 2014; Rostamabadi et al., 2024
Chitosan	Protonated amino groups ($-\text{NH}_3^+$)	Electrostatic and hydrogen bonding yield moderate-high TS (28–46 MPa); hydration strongly plasticizes matrix	Bonilla et al., 2018; Ureña et al., 2023
Alginate (Ca^{2+} cross-linked)	“Egg-box” ionic crosslinks; G-block content	Crosslink density controls modulus and stability; higher Ca^{2+} increases strength but reduces elongation	Rhim, 2014; Nützl et al., 2022; Parreidt et al., 2018
Pullulan	Dense hydrogen bonding; high Tg	Forms strong, flexible, excellent O_2 -barrier films; mechanical and barrier properties decline at high RH	Leathers, 2016; Dewan et al., 2024; Ureña et al., 2023

4. Integrated Molecular perspective

The relationship between polysaccharides' physical properties and their mechanical properties has been extensively studied in recent years across various types of polysaccharides. The results indicate a strong correlation between polysaccharides' mechanical properties and crystalline structure, the amount of hydrogen bonds between molecules and the distribution of molecular nanoparticles. These characteristics are directly correlated to an improvement in the material's tensile strength and Young's modulus due to increased order of the molecular chains and the formation of ordered hydrogen bonding between the molecular chains. Addition of cellulose nanofibers or other nanoparticles further enhances the material's stiffness by allowing for a transfer of the applied stress (Domene-López et al., 2019; Yataka et al., 2020; Yu et al., 2019).

Plasticizers added to the film and the branched nature of some polysaccharides contribute to flexibility of the film by increasing the number of flexible molecular segments and enhancing elongation at failure while reducing cohesion strength and increasing the film's water vapor permeability (Eslami et al., 2023;

Sanyang et al., 2015). Hydrophilic materials composed of polysaccharides have an abundance of hydroxyl groups and charge sites resulting in improved biodegradable and compostable properties however also provide lower moisture resistance and less dimensional stability. Researchers have recently identified that rational design of polysaccharide-based materials through engineered nanocomposites, manipulating hydrogen bond interactions and optimizing cross-linking density will allow designers to balance these competing properties (Rostamabadi et al., 2024; Ahmed et al., 2016). As such, understanding how the molecular characteristics of polysaccharides influence their properties is crucial to develop future generations of polysaccharide-based films that can compete with commercial petroleum-based polymers in terms of performance.

5. Functional Characteristics of Polysaccharide-based Films.

Mechanical properties like tensile strength (TS), elongation at break (EAB) and Young's modulus are highly dependent on both composition and structural arrangement of the polymers. The tensile strength of plasticised starch films usually lies between 5 and 20 MPa and increases with increasing amylose content and crystallinity because of better orientation of molecules and greater intermolecular hydrogen bonding (Pelissari et al., 2017; Müller et al., 2017; Domene-López et al., 2019). Plasticizers improve film flexibility but often lead to a reduction in TS of up to 50% as they disrupt hydrogen bonding and increase free volume within the material (Sanyang et al., 2015; Caicedo et al., 2022). Cellulose based films display considerably higher TS values (up to 90 MPa) mainly because of their β -1,4 linked crystalline micro-fibrils (Rhim et al., 2014). The addition of cellulose nanocrystals (CNC 1 – 5 wt %) into cellulose matrixes improves TS and modulus through an improvement in stress transfer efficiency and a percolated network of nanofillers (Lavrič et al., 2021; Criado et al., 2018). The same effect of adding nanocellulose can be seen in starch-nanocellulose composite films, however the quality of dispersion is critical for achieving maximum potential for reinforcement (Zhang et al., 2023; González et al., 2020).

Thermal stability of polysaccharide films varies widely, depending upon type and degree of substitution of the polymer, with most polysaccharide films degrading at temperatures ranging from 250 to 350°C (Priyadarshi & Rhim, 2020). In contrast, starch and its derivatives degrade at lower temperatures (between 250 and 320°C), primarily due to the lack of crystalline structures that stabilize the thermally stable forms of cellulose (Priyadarshi & Rhim, 2020). Addition of nanocellulose can also delay the degradation onset of the blend by 10–30°C (Syafiq et al., 2023), but the temperature of decomposition remains lower than that of polyethylene (>400°C), which limits the use of these materials in applications requiring high temperature processing.

Barrier properties are the main limit of polysaccharide-based films. Despite the low oxygen permeability of the films under dry conditions due to the presence of tightly packed hydrogen bonded networks (Ureña et al., 2023; Jarvis et al., 2023), the water vapor permeability (WVP) is normally 2–10 times greater than that of low-density polyethylene. For example, typical WVP values of starch films are $5\text{--}15 \times 10^{-10} \text{ g} \cdot \text{m} / \text{m}^2 \cdot \text{s} \cdot \text{Pa}$ whereas those of low-density polyethylene are approximately $0.5\text{--}1 \times 10^{-10} \text{ g} \cdot \text{m} / \text{m}^2 \cdot \text{s} \cdot \text{Pa}$. At RH above 60–70%, the moisture induced plasticization of the films will disrupt the intermolecular interaction, leading to accelerated diffusion of vapors. Incorporating CNC or nanoclays into polysaccharide-based films can reduce WVP by 40–60% using tortuous diffusion pathways (Ali et al., 2018; Criado et al., 2018), but the challenge of maintaining humidity stability over time remains.

6. Modification and reinforcement of plastics

Modification and reinforcement of polysaccharide films are necessary because, despite inherent biodegradability and film forming potential, they suffer from poor mechanical properties and high moisture sensitivity. The most common method for improving flexibility is to utilize plasticizers. Increased amounts of glycerol (20–40wt%) can lead to a 30–50% reduction in tensile strength (TS) and increase elongation at break due to the interruption of hydrogen bonds and increased mobility of chains (Saberli et al., 2017; Pelissari et al., 2017; Caicedo et al., 2022). However, too much plasticizer can also result in an increase in water vapor permeability (WVP) and moisture absorption (Eslami et al., 2023).

The application of chemical cross-links increases the intermolecular cohesive forces and reduces the degree of moisture absorption. Citric acid (CA) is one example of an environmentally friendly cross-linking agent which creates ester linkages with hydroxyl groups. This results in an increase in TS (15–40%), a decrease in solubility, and a significant reduction in WVP (up to 50%) (Zhang et al., 2023; Wu et al., 2019; Khadsai et al., 2024). Alginate-based systems exhibit improved TS (approximately 25–35%) and dimensionally stable properties when utilizing Ca^{2+} -mediated ionic cross-linking to create "egg-box" type networks; however, this can result in reduced flexibility if the cross-link density is excessive (Syarifuddin et al., 2025; Rhim, 2014).

Reinforcing with nanocomposites represents the most effective approach to impart multiple functions into polysaccharide films. The addition of 1–5 wt.% of cellulose nanocrystals (CNC) or nanofibers can be used to produce materials with significantly improved TS (30–100%) and WVP (15–60%) via mechanisms including stress transfer and tortuous diffusion pathways (El Miri et al., 2015; Criado et al., 2018; Noshirvani et al., 2018; Calvino et al., 2020). Nanoclay addition can also be utilized to produce materials with enhanced barrier properties by creating longer diffusion paths, however, the quality of dispersion and the extent of interfacial compatibility represent major factors influencing successful utilization of these materials (Muñoz-Gimena et al., 2023). Overall, hybrid approaches, including moderate plasticization in combination with controlled cross-linking and the incorporation of dispersed nanofillers, offer the best route to provide both the mechanical properties and barrier properties required for polysaccharide based packaging materials while maintaining biodegradable

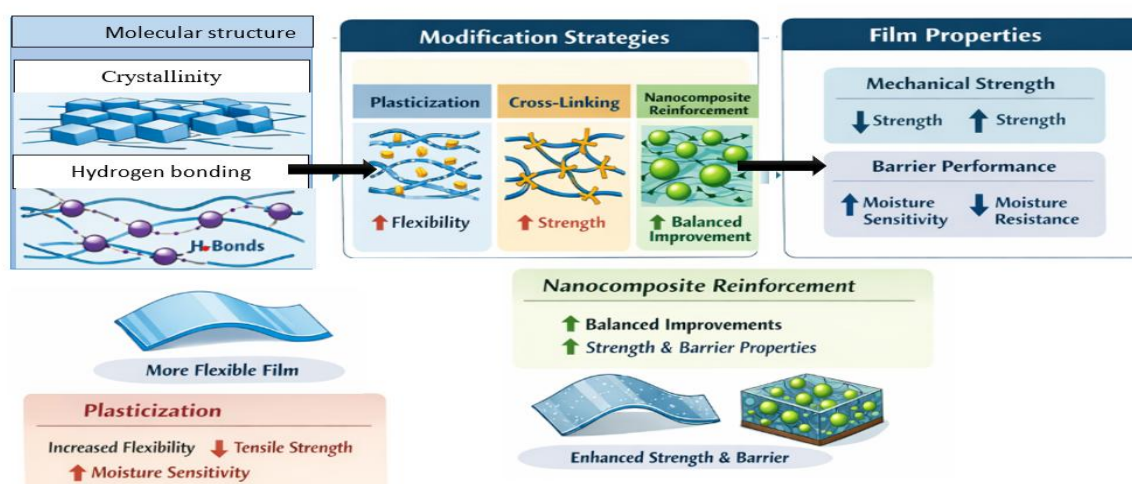


Figure 2: Structure Modification Performance Relationship in Polysaccharide-Based Films. Schematic illustration showing the influence of molecular structure (crystallinity and hydrogen bonding), modification strategies (plasticization, cross-linking, nanocomposite reinforcement), and resulting changes in mechanical strength and barrier performance. Nanocomposite reinforcement provides the most balanced improvement, whereas plasticization primarily enhances flexibility at the expense of tensile strength and moisture resistance

7. Application of polysaccharide-based polymers

The application of polysaccharide film is progressing at a fast pace toward the use in medical and agricultural sectors. For example, starch, cellulose, chitosan, alginate, pectin and pullulan are widely used as edible coating, primary wrap and active packaging material in food systems (Cazón et al., 2017; Li et al., 2024; Dhalsamant et al., 2025) because they have excellent oxygen barrier property when there is less than 60% RH. This is attributed to the strong H-bonded network of these materials which is comparable to that of commercial synthetic polymer at low RH (Janik et al., 2022). The functionalized polysaccharide films by incorporation of antimicrobials, polyphenols, natural antioxidants etc. enhance the microbial inhibition and oxidative stability thereby extend the shelf life of fresh produce such as

fruit, vegetable, meat etc. (Criado et al., 2011; Zhu, 2021; Periyasamy et al., 2025). Nevertheless, the high water vapor permeability and the moisture sensitivity of polysaccharide film are still major hurdles.

For biomedical applications, the majority of polysaccharides used include chitosan and alginate, owing to their biocompatibility, biodegradability and adjustable degradation behavior. Chitosan film and scaffold provide an environment conducive to wound healing, via its inherent antimicrobial activity, hemostatic ability, and cell adhesion support for tissue regeneration (Baharlouei et al., 2022; Ahsan et al., 2018; Rezaei et al., 2021; Gholap et al., 2024). Cross-linking alginate provides a matrix for controlled drug delivery and wet wound environment.

In the agricultural sector, polysaccharide composite films are utilized as biodegradable mulching films, seed coating films and controlled-release fertilizer films (Dada et al., 2025; Menossi et al., 2021; Ciaramitaro et al., 2024). While properly designed mulch films can prevent the formation of plastic debris in the soil, maintain crop yields, and reduce plastic usage in the long term, the mulch films must be durable enough to withstand environmental stresses and have lower costs than current alternatives.

8. Sustainability & Life Cycle Assessment

Sustainability is an important factor in developing polysaccharide-based biodegradable films that will provide alternatives to petroleum-based plastics by providing a substitute to fossil resources and reduce plastic waste in landfills and oceans. In contrast to polyethylene and polypropylene which come from petrochemical feedstocks, polysaccharides are generated from renewable biomass sources such as crops, forest residues and agri-food waste streams (Kocira et al., 2021; Hassan et al., 2024). Life cycle assessments (LCAs), which evaluate all environmental impacts associated with the production, distribution and disposal of products have shown that fossil energy requirements and greenhouse gas (GHG) emissions are generally lower for bio-based plastics than for traditional plastics, particularly when secondary raw materials or waste biomass are employed (Tonini et al., 2021; Benavides et al., 2020). While the climate advantages of using bioplastics are beneficial, there may be offsets due to the need for agricultural inputs, fertilizers, and the energy required for processing of the materials. If not managed correctly, this can increase eutrophication and acidification impacts (Senila et al., 2024; Dada et al., 2025).

One of the most significant factors influencing the sustainability of film is its end-of-life performance. Biodegradable films typically degrade rapidly during industrial composting, while they tend to degrade at a much slower rate when deposited into soils, where their decomposition is also very climate dependent (Van Roijen et al., 2022; Sintim et al., 2020). The actual method of disposal (i.e., composting, land application, landfilling, anaerobic digestion) has a large impact on the results of LCAs and carbon balances (Montegiove et al., 2024; Falzarano et al., 2024). Furthermore, adding nanofillers and/or other additives to biodegradable films introduce ecotoxicity and migration issues that need to be assessed.

Polysaccharide-based biodegradable films have a number of possible environmental benefits compared to petroleum-based polymers like polyethylene and polypropylene. Since these materials are produced using renewable sources of biomass, such as agricultural residues and marine biopolymers, their production can lead to the reduction of fossil resources and decreased greenhouse gases. The evaluation of the carbon footprint of bio-based films is often found to decrease in life cycle assessment, especially when feedstocks are obtained as waste. The benefits of overall sustainability, however, are highly contingent on the products used in agricultural production, the use of energy during the processing phases, and the presence of effective end-of-life management systems. Thus, detailed sustainability assessments, incorporating sources of feedstock, material processing, and disposal efforts, are the necessary measures to make biodegradable films a practical contribution to the principles of the circular economy.

9. Research Gaps

Despite great progress made in biodegradable film technologies based on polysaccharides, there are still a number of important research gaps that hinder large scale industrial implementation. A major problem has been the sensitivity to moisture under typical environmental conditions. While many studies have shown that polysaccharide-based biodegradable films can provide high oxygen barrier resistance at moderate humidities (typically <60-70 % RH) (Shankar , 2016; Cazon et al., 2017), they experience significant loss of mechanical strength and barrier function as relative humidity increases above 60-70%. This occurs primarily through water induced plasticization and the breakdown of hydrogen bond networks (Shankar & Rhim, 2018; Cazon et al., 2017).

Another limitation of current research has been the lack of established test standards. The mechanical and barrier properties of polysaccharide-based biodegradable films are typically measured using various conditioning environments, film thickness, and plasticizers. Therefore, direct comparisons of data from different studies are difficult if not impossible (Cazon et al., 2017). Additionally, while nanocomposites (Criado et al., 2018; Priyadarshi & Rhim, 2020) and crosslinking (Priyadarshi & Rhim, 2020) techniques are highly effective at increasing tensile strength and reducing water vapor permeability, systematic relationships between crosslink density, crystallinity, and biodegradation kinetics have not been extensively studied. Increased structural stabilization of polysaccharide-based biodegradable films may be achieved through these methods but it is likely to occur at the expense of the degradation rate of the films. Few studies have quantified this relationship. Finally, scaling up the manufacturing process for polysaccharide-based biodegradable films is also challenging. Most research conducted on biodegradable films has utilized a solvent casting technique. However, industrial manufacturing typically uses either blow-film processing or extrusion. As such, there is a need to study the thermally sensitive nature of these materials during melt processing (Priyadarshi & Rhim, 2020).

Although life cycle assessments have indicated that biodegradable films have lower greenhouse gas emissions than polyethylene (Benavides et al., 2020), the results have depended heavily on the origin of the feedstocks used, land use, and energy input (Benavides et al., 2020; Udara et al., 2025).

Scalability and Processing on an Industrial Level.

The most significant obstacle to commercialization of polysaccharide-based films is the scaling down in terms of both technology and scale of the fabrication methods to industrial manufacturing methods. Solvent casting techniques are used in the majority of experimental research, and enable strict control of film composition, but cannot be economically produced on a large scale. Conversely, industrial packaging material is normally melt-processed through extrusion, injection molding or blow-film processing. Most polysaccharides have low thermal stability and low process margins, rendering the processing of most polysaccharides extremely difficult in a normal polymer manufacturing environment. Thus, subsequent studies would focus on designing thermally stable compositions, compatible plasticizer systems, and processable strategies that enable the production of biodegradable polysaccharide films with the help of the existing industrial equipment.

10. Conclusion

To summarize, biodegradable films made of polysaccharides offer considerable promise as long-term replacements for non-renewable short-life cycle products, especially in the packaging of dry foods, biomedical supplies, and controlled environments used in agriculture. The addition of nanocomposite reinforcement and cross-linking using renewable resources has significantly enhanced both the mechanical properties and barrier performance of these films; however, there are still several challenges that need to be overcome prior to commercialization. These include: hydrophilic nature (water attraction), moisture sensitivity, limitations with current processing methods used in the food industry, and comparative costs. To bridge this gap and enable polysaccharide-based films to transition from an innovative product being tested at the laboratory scale to a commercially viable product for large-scale production under a circular bioeconomic model, it will be necessary to provide for standardized testing of their performance, coupled degradation analysis of their structures, development of new scalable processing technologies and use of waste products as feedstocks.

References

- Ahmed, S. and Ikram, S., 2016. Chitosan and gelatin based biodegradable packaging films with UV-light protection. *Journal of Photochemistry and Photobiology B: Biology*, 163, pp.115–124. <https://doi.org/10.1016/j.jphotobiol.2016.08.023>
- Ahsan, S.M., Thomas, M., Reddy, K.K., Sooraparaju, S.G., Asthana, A. and Bhatnagar, I., 2018. Chitosan as biomaterial in drug delivery and tissue engineering. *International Journal of Biological Macromolecules*, 110, pp.97–109. <https://doi.org/10.1016/j.ijbiomac.2017.08.140>
- Ali, A., Xie, F., Yu, L., Liu, H., Meng, L., Khalid, S. and Chen, L., 2018. Preparation and characterization of starch-based composite films reinforced by polysaccharide-based crystals. *Composites Part B: Engineering*, 133, pp.122–128. <https://doi.org/10.1016/j.compositesb.2017.09.017>
- Andrady, A.L., 2011. Microplastics in the marine environment. *Marine Pollution Bulletin*, 62(8), pp.1596–1605. <https://doi.org/10.1016/j.marpolbul.2011.05.030>
- Arachchige, U. and Nirmal, C., 2025. Life cycle assessment (LCA) of bio-based polymers vs. conventional plastics in automotive engineering. pp.207–220.
- Avérous, L., 2004. Biodegradable multiphase systems based on plasticized starch: A review. *Polymer Reviews*, 44, pp.231–274. <https://doi.org/10.1081/MC-200029326>
- Azeredo, H.M.C., Mattoso, L.H.C. and McHugh, T.H., 2011. Nanocomposites in food packaging: A review. In: *Advances in Diverse Industrial Applications of Nanocomposites*. <https://doi.org/10.5772/14437>
- Baharlouei, P. and Rahman, A., 2022. Chitin and chitosan: Prospective biomedical applications in drug delivery, cancer treatment, and wound healing. *Marine Drugs*, 20(7), 460. <https://doi.org/10.3390/md20070460>
- Ballesteros-Mártinez, L., Pérez-Cervera, C. and Andrade-Pizarro, R., 2020. Effect of glycerol and sorbitol concentrations on mechanical, optical, and barrier properties of sweet potato starch film. *NFS Journal*, 20, pp.1–9. <https://doi.org/10.1016/j.nfs.2020.06.002>
- Beckham, G.T., Matthews, J.F., Peters, B., Bomble, Y.J., Himmel, M.E. and Crowley, M.F., 2011. Molecular-level origins of biomass recalcitrance: Decrystallization free energies for four common cellulose polymorphs. *The Journal of Physical Chemistry B*, 115(14), pp.4118–4127. <https://doi.org/10.1021/jp1106394>
- Benavides, P., Lee, U. and Zare-Mehrjerdi, O., 2020. Life cycle greenhouse gas emissions and energy use of polylactic acid, bio-derived polyethylene, and fossil-derived polyethylene. *Journal of Cleaner Production*, 277, 124010. <https://doi.org/10.1016/j.jclepro.2020.124010>
- Bonilla, J. and Sobral, P.J.A., 2018. Gelatin–chitosan edible film activated with boldo extract for improving microbiological and antioxidant stability of sliced Prato cheese. *International Journal of Food Science & Technology*. <https://doi.org/10.1111/ijfs.14032>
- Bonilla, J. and Sobral, P.J.A., 2020. Disintegrability under composting conditions of films based on gelatin, chitosan and/or sodium caseinate containing boldo-of-Chile leaf extract. *International Journal of Biological Macromolecules*, 151, pp.178–185. <https://doi.org/10.1016/j.ijbiomac.2020.02.051>
- Bourtoom, T., 2008. Edible films and coatings: Characteristics and properties. *International Food Research Journal*, 15, pp.237–248.
- Caicedo, C., Díaz-Cruz, C.A., Jiménez-Regalado, E.J. and Aguirre-Loredo, R.Y., 2022. Effect of plasticizer content on mechanical and water vapor permeability of maize starch/PVOH/chitosan composite films. *Materials*, 15(4), 1274. <https://doi.org/10.3390/ma15041274>
- Cazón, P., Velazquez, G. and Vázquez, M., 2019. Novel composite films from regenerated cellulose–glycerol–polyvinyl alcohol: Mechanical and barrier properties. *Food Hydrocolloids*, 89, pp.481–491. <https://doi.org/10.1016/j.foodhyd.2018.11.012>
- Cazón, P., Velazquez, G., Ramírez, J.A. and Vázquez, M., 2017. Polysaccharide-based films and coatings for food packaging: A review. *Food Hydrocolloids*, 68, pp.136–148. <https://doi.org/10.1016/j.foodhyd.2016.09.009>
- Chen, Y. and Shull, K.R., 2023. Controlling the properties of thermoplastic starch films with hydrogen bonding plasticizers. *Carbohydrate Polymer Technologies and Applications*, 5, 100291. <https://doi.org/10.1016/j.carpta.2023.100291>

- Criado, M.P., Hossain, F., Salmieri, S. and Lacroix, M., 2018. Nanocellulose in food packaging. In: *Nanocellulose in Food Packaging Applications*. <https://doi.org/10.1002/9781119160243.ch10>
- Dewan, M. and Islam, M.N., 2024. Pullulan-based films: Unveiling its multifaceted versatility for sustainability. *Advances in Polymer Technology*, 2024, Article ID 2633384. <https://doi.org/10.1155/2024/2633384>
- Domene-López, D., García-Quesada, J.C., Martín-Gullón, I. and Montalbán, M.G., 2019. Influence of starch composition and molecular weight on physicochemical properties of biodegradable films. *Polymers*, 11(7), 1084. <https://doi.org/10.3390/polym11071084>
- Draget, K., Smidsrød, O. and Skjåk-Bræk, G., 2005. Alginates from algae. In: *Biopolymers Online*. <https://doi.org/10.1002/3527600035.bpol6008>
- Draget, K.I., Skjåk-Bræk, G. and Smidsrød, O., 1994. Alginic acid gels: The effect of alginate chemical composition and molecular weight. *Carbohydrate Polymers*, 25(1), pp.31–38. [https://doi.org/10.1016/0144-8617\(94\)90159-7](https://doi.org/10.1016/0144-8617(94)90159-7)
- European Commission, 2018. A sustainable bioeconomy for Europe: Strengthening the connection between economy, society and the environment. Available at: <https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52018DC0673>
- Falzarano, M., Marin, A., Cabedo, L., Poletini, A., Pomi, R., Rossi, A. and Zonfa, T., 2024. Alternative end-of-life options for disposable bioplastic products: Degradation and ecotoxicity assessment in compost and soil. *Chemosphere*, 362, 142648. <https://doi.org/10.1016/j.chemosphere.2024.142648>
- Geyer, R., Jambeck, J.R. and Law, K.L., 2017. Production, use, and fate of all plastics ever made. *Science Advances*, 3, e1700782. <https://doi.org/10.1126/sciadv.1700782>
- Gholap, A.D., Rojekar, S., Kapare, H.S., Vishwakarma, N., Raikwar, S., Garkal, A., Mehta, T.A., Jadhav, H., Prajapati, M.K. and Annapure, U., 2024. Chitosan scaffolds: Expanding horizons in biomedical applications. *Carbohydrate Polymers*, 323, 121394. <https://doi.org/10.1016/j.carbpol.2023.121394>
- González, K., Iturriaga, L., González, A., Eceiza, A. and Gabilondo, N., 2020. Improving mechanical and barrier properties of thermoplastic starch and polysaccharide nanocrystals nanocomposites. *European Polymer Journal*, 123, 109415. <https://doi.org/10.1016/j.eurpolymj.2019.109415>
- Gupta, A., Khodayari, A., van Duin, A.C.T., Hirn, U., Van Vuure, A.W. and Seveno, D., 2022. Cellulose nanocrystals: Tensile strength and failure mechanisms revealed using reactive molecular dynamics. *Biomacromolecules*, 23(6), pp.2243–2254. <https://doi.org/10.1021/acs.biomac.1c01110>
- Hadi, A., Nawab, A., Alam, F. and Zehra, K., 2022. Sustainable alginate/aloë vera composite biodegradable films reinforced with carboxymethyl cellulose and hydroxypropyl methylcellulose. *Polymer Composites*.
- Hassan, F., Mu, B. and Yang, Y., 2024. Natural polysaccharides and proteins-based films for potential food packaging and mulch applications: A review. *International Journal of Biological Macromolecules*, 261, 129628. <https://doi.org/10.1016/j.ijbiomac.2024.129628>
- Jahan, A.S.S. and Haroon, M.H., 2025. Extraction of chitosan from shrimp exoskeleton and development of eco-friendly bioplastics: A sustainable waste-to-resource approach. In: *Proceedings of the 2nd International Conference on University–Industry Collaborations for Sustainable Development (ICSD 2025)*, Colombo, Sri Lanka. Available at: <https://colomboconference.org/wp-content/uploads/2025/09/colombo-proceeding-.pdf>
- Jambeck, J.R., Geyer, R., Wilcox, C., Siegler, T.R., Perryman, M., Andrady, A., Narayan, R. and Law, K.L., 2015. Plastic waste inputs from land into the ocean. *Science*, 347(6223), pp.768–771. <https://doi.org/10.1126/science.1260352>
- Jarvis, M.C., 2023. Hydrogen bonding and other non-covalent interactions at the surfaces of cellulose microfibrils. *Cellulose*, 30, pp.667–687. <https://doi.org/10.1007/s10570-022-04954-3>
- Jørgensen, T.E., Sletmoen, M., Draget, K.I. and Stokke, B.T., 2007. Influence of oligoguluronates on alginate gelation, kinetics, and polymer organization. *Biomacromolecules*, 8(8), pp.2388–2397. <https://doi.org/10.1021/bm070208d>

- Klemm, D., Heublein, B., Fink, H.P. and Bohn, A., 2005. Cellulose: Fascinating biopolymer and sustainable raw material. *Angewandte Chemie International Edition*, 44(22), pp.3358–3393. <https://doi.org/10.1002/anie.200460587>
- Kocira, A., Kozłowicz, K., Panasiewicz, K., Staniak, M., Szpunar-Krok, E. and Hortyńska, P., 2021. Polysaccharides as edible films and coatings: Characteristics and influence on fruit and vegetable quality—A review. *Agronomy*, 11(5), 813. <https://doi.org/10.3390/agronomy11050813>
- Kong, M., Chen, X.G., Xing, K. and Park, H.J., 2010. Antimicrobial properties of chitosan and mode of action: A state-of-the-art review. *International Journal of Food Microbiology*, 144(1), pp.51–63. <https://doi.org/10.1016/j.ijfoodmicro.2010.09.012>
- Kopplin, G., Lervik, A., Draget, K.I. and Aachmann, F.L., 2021. Alginate gels crosslinked with chitosan oligomers: A systematic investigation into alginate block structure and chitosan oligomer interaction. *RSC Advances*, 11(23), pp.13780–13798. <https://doi.org/10.1039/d1ra01003d>
- Lavrič, G., Oberlintner, A., Filipova, I., Novak, U., Likozar, B. and Vrabič-Brodnjak, U., 2021. Functional nanocellulose, alginate and chitosan nanocomposites designed as active film packaging materials. *Polymers*, 13(15), 2523. <https://doi.org/10.3390/polym13152523>
- Leathers, T.D., 2003. Biotechnological production and applications of pullulan. *Applied Microbiology and Biotechnology*, 62(5–6), pp.468–473. <https://doi.org/10.1007/s00253-003-1386-4>
- Leslie, H.A., van Velzen, M.J.M., Brandsma, S.H., Vethaak, A.D., Garcia-Vallejo, J.J. and Lamoree, M.H., 2022. Discovery and quantification of plastic particle pollution in human blood. *Environment International*, 163, 107199. <https://doi.org/10.1016/j.envint.2022.107199>
- Li, S., Ren, Y., Hou, Y., Zhan, Q., Jin, P., Zheng, Y. and Wu, Z., 2024. Polysaccharide-based composite films: Promising biodegradable food packaging materials. *Foods*, 13(22), 3674. <https://doi.org/10.3390/foods13223674>
- McMullen, R.L., Ozkan, S. and Gillece, T., 2022. Physicochemical properties of cellulose ethers. *Cosmetics*, 9(3), 52. <https://doi.org/10.3390/cosmetics9030052>
- Menossi, M., Cisneros, M. and Alvarez, V.A., 2021. Current and emerging biodegradable mulch films based on polysaccharide bio-composites: A review. *Agronomy for Sustainable Development*, 41, 53. <https://doi.org/10.1007/s13593-021-00685-0>
- Miyamoto, H., Yamane, C., Seguchi, M. and Okajima, K., 2009. Structure and properties of cellulose–starch blend films regenerated from aqueous sodium hydroxide solution. *Food Science and Technology Research*, 15, pp.403–412. <https://doi.org/10.3136/fstr.15.403>
- Molavi, H., Behfar, S., Shariati, M.A., Kaviani, M. and Atarod, S., 2018. A review on biodegradable starch-based film. *Journal of Microbiology, Biotechnology and Food Sciences*. <https://doi.org/10.15414/jmbfs.2015.4.5.456-461>
- Montegiove, N., Petrucci, R., Bacci, L., Gigliotti, G., Puglia, D., Torre, L. and Pezzolla, D., 2024. Evaluation of biogas production from anaerobic digestion of biopolymeric films and potential environmental implications. *Sustainability*, 16(22), 10146. <https://doi.org/10.3390/su162210146>
- Muñoz-Bonilla, A., Cerrada, M. and Fernández-García, M., 2013. Antimicrobial activity of chitosan in food, agriculture and biomedicine. In: *Antimicrobial Polymers*. <https://doi.org/10.1039/9781782624998-00022>
- Nützl, M., Schrottenbaum, M., Müller, T. and Müller, R., 2022. Mechanical properties and chemical stability of alginate-based anisotropic capillary hydrogels. *Journal of the Mechanical Behavior of Biomedical Materials*, 134, 105397. <https://doi.org/10.1016/j.jmbbm.2022.105397>
- PlasticsEurope, 2023. *Plastics – The Facts 2023*. Available at: <https://plasticseurope.org/knowledge-hub/plastics-the-fast-facts-2023/>
- Rezaei, F.S., Sharifianjazi, F., Esmailkhanian, A. and Salehi, E., 2021. Chitosan films and scaffolds for regenerative medicine applications: A review. *Carbohydrate Polymers*, 273, 118631. <https://doi.org/10.1016/j.carbpol.2021.118631>
- Rhim, J.W., 2004. Physical and mechanical properties of water resistant sodium alginate films. *LWT – Food Science and Technology*, 37, pp.323–330. <https://doi.org/10.1016/j.lwt.2003.09.008>

- Rhim, J.W., Park, H.M. and Ha, C.S., 2013. Bio-nanocomposites for food packaging applications. *Progress in Polymer Science*, 38(10–11), pp.1629–1652. <https://doi.org/10.1016/j.progpolymsci.2013.05.008>
- Rostamabadi, H. et al., 2024. Recent trends in the application of films and coatings based on starch, cellulose, chitin, chitosan, xanthan, gellan, pullulan, Arabic gum, alginate, pectin, and carrageenan in food packaging. *Food Frontiers*. <https://doi.org/10.1002/fft2.342>
- Sanyang, M.L., Sapuan, S.M., Jawaid, M., Ishak, M.R. and Sahari, J., 2015. Effect of plasticizer type and concentration on tensile, thermal and barrier properties of biodegradable films based on sugar palm (*Arenga pinnata*) starch. *Polymers*, 7(6), pp.1106–1124. <https://doi.org/10.3390/polym7061106>
- Senila, L., Kovacs, E., Resz, M.A., Senila, M., Becze, A. and Roman, C., 2024. Life cycle assessment (LCA) of bioplastics production from lignocellulosic waste (study case: PLA and PHB). *Polymers*, 16(23), 3330. <https://doi.org/10.3390/polym16233330>
- Senturk Parreidt, T., Müller, K. and Schmid, M., 2018. Alginate-based edible films and coatings for food packaging applications. *Foods*, 7(10), 170. <https://doi.org/10.3390/foods7100170>
- Shankar, S. and Rhim, J.W., 2016. Preparation of nanocellulose from micro-crystalline cellulose: The effect on the performance and properties of agar-based composite films. *Carbohydrate Polymers*, 135, pp.18–26. <https://doi.org/10.1016/j.carbpol.2015.08.082>
- Sintim, H.Y. et al., 2020. In situ degradation of biodegradable plastic mulch films in compost and agricultural soils. *Science of the Total Environment*, 727, 138668. <https://doi.org/10.1016/j.scitotenv.2020.138668>
- Siracusa, V., Rocculi, P., Romani, S. and Dalla Rosa, M., 2008. Biodegradable polymers for food packaging: A review. *Trends in Food Science & Technology*, 19(12), pp.634–643. <https://doi.org/10.1016/j.tifs.2008.07.003>
- Syafiq, R.M.O., Ilyas, R.A., Kumar, L.R., Al-Oqla, F., Yusoff, N., Zuhri, M., Atiqah, A., Thiagamani, S.M.K., Punia Bangar, S., Barile, C. and Sapuan, S.M., 2023. Corn starch nanocomposite films reinforced with nanocellulose. *Physical Sciences Reviews*, 9. <https://doi.org/10.1515/psr-2022-0011>
- Tarique, J., Sapuan, S.M. and Khalina, A., 2021. Effect of glycerol plasticizer loading on the physical, mechanical, thermal and barrier properties of arrowroot (*Maranta arundinacea*) starch biopolymers. *Scientific Reports*, 11, 13900. <https://doi.org/10.1038/s41598-021-93094-y>
- Tharanathan, R.N., 2003. Biodegradable films and composite coatings: Past, present, and future. *Trends in Food Science & Technology*, 14, pp.71–78. [https://doi.org/10.1016/S0924-2244\(02\)00280-7](https://doi.org/10.1016/S0924-2244(02)00280-7)
- Thompson, R.C., Olsen, Y., Mitchell, R.P., Davis, A., Rowland, S.J., John, A.W.G., McGonigle, D. and Russell, A.E., 2004. Lost at sea: Where is all the plastic? *Science*, 304(5672), p.838. <https://doi.org/10.1126/science.1094559>
- Tonini, D., García-Gutierrez, P. and Nessi, S., 2021. Environmental effects of plastic waste recycling: Focus on climate change effects. European Commission Joint Research Centre.
- Tsochatzis, E.D., Vidal, N.P., Bai, W., Diamantidou, D., Theodoridis, G. and Martinez, M.M., 2023. Untargeted screening and in silico toxicity assessment of semi- and non-volatile compounds migrating from polysaccharide-based food contact materials. *Food Chemistry*, 425, 136499. <https://doi.org/10.1016/j.foodchem.2023.136499>
- Ureña, M. et al., 2023. Potential of polysaccharides for food packaging applications. Part 1/2: Functional properties of polysaccharide coatings. *Food Hydrocolloids*, 144, 108955. <https://doi.org/10.1016/j.foodhyd.2023.108955>
- Van Roijen, E.C. and Miller, S.A., 2022. A review of bioplastics at end-of-life: Linking experimental biodegradation studies and life cycle impact assessments. *Resources, Conservation & Recycling*, 181, 106236. <https://doi.org/10.1016/j.resconrec.2022.106236>
- Wang, J. et al., 2024. Structuring restricted amorphous molecular chains in the reinforced cellulose film by uniaxial stretching. *Carbohydrate Polymers*, 337, 122088. <https://doi.org/10.1016/j.carbpol.2024.122088>

- Wang, S. et al., 2023. Delivery of curcumin in a carboxymethyl cellulose and hydroxypropyl methyl cellulose carrier: Physicochemical properties and biological activity. *International Journal of Biological Macromolecules*, 239, 124203. <https://doi.org/10.1016/j.ijbiomac.2023.124203>
- Wright, S.L., Thompson, R.C. and Galloway, T.S., 2013. The physical impacts of microplastics on marine organisms: A review. *Environmental Pollution*, 178, pp.483–492. <https://doi.org/10.1016/j.envpol.2013.02.031>
- Zhang, D., Fang, Z., Hu, S. and Qiu, X., 2024. High aspect ratio cellulose nanofibrils with low crystallinity for strong and tough films. *Carbohydrate Polymers*, 346, 122630. <https://doi.org/10.1016/j.carbpol.2024.122630>
- Zhang, J. et al., 2023. Effects of different sources of cellulose on mechanical and barrier properties of thermoplastic sweet potato starch films. *Industrial Crops and Products*, 194, 116358. <https://doi.org/10.1016/j.indcrop.2023.116358>
- Zhang, L. et al., 2024. Effects of amylose and amylopectin fine structure on the thermal, mechanical and hydrophobic properties of starch films. *International Journal of Biological Macromolecules*, 282, 137018. <https://doi.org/10.1016/j.ijbiomac.2024.137018>
- Zhou, X. et al., 2024. Nanofillers in novel food packaging systems and their toxicity issues. *Foods*, 13(13), 2014. <https://doi.org/10.3390/foods13132014>
- Zhu, F., 2021. Polysaccharide-based films and coatings for food packaging: Effect of added polyphenols. *Food Chemistry*, 359, 129871. <https://doi.org/10.1016/j.foodchem.2021.129871>

ICRES26_060

**VALORIZATION OF BIOMASS ASH FROM INDUSTRIAL WASTE AS A
CIRCULAR FERTILIZER RESOURCE FOR SUSTAINABLE AGRICULTURE****H.P.K.D. Dilshani, K.H.P. Madusanka, H.P.A.M. Siriwardana, T.M.D.P. Thennakoon****Department of Civil Engineering, Faculty of Engineering, University of Sri Jayewardenepura, Mattegoda,
Sri Lanka.***Correspondence E-mail: dilshanthennakoon@sjp.ac.lk, TP: +94717299950*

Abstract: Biomass ash generated by the combustion processes in sectors like cinnamon oil refining is routinely discarded into landfills as mere waste, driving a cycle of environmental degradation and loss of resources. However, because this ash contains important mineral nutrients, it can potentially serve as a highly effective soil amendment. Reusing it for agricultural purposes, such as in chili (*Capsicum annum*) cultivation, directly supports the principles of a circular economy. This study examines the physicochemical properties, agronomic performance, and circular reuse potential of biomass ash derived from a Sri Lankan industrial process, with a focus on its application as a fertilizer replacement. Material characterization included pH, electrical conductivity (EC), density, and water holding capacity (WHC). Controlled pot experiments were done to evaluate the effects of graded ash applications on soil chemical properties and plant growth. Results showed that this alkaline ash (pH 11.85 - 12.28) improved soil pH buffering when applied at optimized rates. Despite high EC levels (24.8 - 28.1 mS/cm), its low bulk density (0.65 - 0.67 g/cm³) and high WHC (80.89 - 98.63%), enhanced soil aeration and moisture retention. Consequently, optimized ash application resulted in significant, ratio-dependent increases in plant height and leaf area compared to controls, without adverse impacts from salinity. Importantly, ash reuse redirects a waste stream into a value-added agricultural input, contributing to zero-waste objectives. This research demonstrates a practical pathway for industrial waste valorization, linking waste management with sustainable agriculture. It provides evidence that treated biomass ash can be integrated into farming systems as a resource reuse strategy, contributing to circular resource flows and improved agronomic outcomes. These findings are significant for stakeholders aiming to accelerate transitions towards resource efficiency. Future work will focus on assessing long-term soil health impacts, exploring scaling opportunities, and evaluating the suitability of this highly alkaline amendment across other crop species.

Keywords: Biomass ash valorization; circular economy; resource reuse; sustainable agriculture; industrial waste reuse

1. Introduction

The global shift toward renewable energy sources has significantly increased the reliance on biomass combustion for industrial heat and power. While this transition is crucial for reducing dependence on fossil fuels, it has inevitably created a substantial secondary waste stream: biomass ash. Proper management of this by-product is becoming an increasingly pressing concern. Currently, a significant portion of this ash is treated simply as waste and disposed of in landfills (Reijnders, 2004). This practice is inherently unsustainable. Not only does it occupy valuable land space and contribute to environmental degradation, including unauthorized dumping and airborne dust issues, but it also represents a substantial loss of potential resources, failing to align with the principles of a circular economy.

In the specific context of Sri Lanka, the cinnamon industry serves as a vital economic engine, producing goods renowned for both culinary and preventive health applications (Kowalska et al., 2021). Cinnamon oil is extracted from both the leaves and bark of the plant. After the extraction process, the residual parts (spent wood and leaves) are utilized as fuel for the necessary combustion procedures (Department of Cinnamon Development, 2024). Consequently, the cinnamon oil refinery industry generates significant amounts of biomass ash as a by-product. At present, the common practice in Sri Lanka is to treat this ash as waste. This leads to considerable environmental and economic concerns, as improper disposal is environmentally detrimental, causes shifts in soil alkalinity, and is increasingly challenged by stricter environmental regulations (Pugliese et al., 2014; Silva et al., 2019). There is a critical and pressing need to develop sustainable waste management practices for this specific industrial by-product.

However, recognizing biomass ash as a liability overlooks its intrinsic value. Biomass ash is a concentrated source of the inorganic elements originally taken up by the plant during its growth (Vassilev et al., 2017). Existing literature highlights the potential of using ash as an effective and economical soil amendment (Albuquerque et al., 2021). Studies show that average wood ash contains beneficial elements such as potassium, phosphorus, and magnesium (Serafimova et al., 2011), making it a potential substitute for mineral lime and potassium fertilizers, which typically present an N-P-K profile of approximately 0-1-3. Furthermore, ash additions can stimulate the mineralization of organic matter by microorganisms, which can further increase nutrient availability in the soil (Risse and Gaskin, 2016). Importantly, soil tests have demonstrated that wood ash typically increases soil pH, making it highly effective at neutralizing soil acidity (Ohno & Erich, 1990). While these benefits are documented for general wood ash, there remains a critical knowledge gap regarding the specific characterization and agronomic potential of the niche feedstock generated by Sri Lankan cinnamon refineries. It is essential to determine the specific nutrient profile and pH of this unique ash, similar to how soil pH tests are routinely conducted at least annually in the cinnamon industry to manage acidity levels.

Therefore, this study seeks to address this gap by comprehensively characterizing the specific physicochemical properties of cinnamon refinery ash. The primary objective is to evaluate its efficacy as a circular soil amendment through controlled pot experiments. By thoroughly investigating its composition and impact on plant growth, this research aims to transform an environmental liability into a valuable agricultural asset. Ultimately, this work seeks to provide actionable insights for transitioning the Sri Lankan cinnamon industry toward greater resource efficiency and sustainability, replacing synthetic fertilizer use and promoting sustainable waste management frameworks. Specifically, this study tests the hypothesis that the controlled application of alkaline cinnamon biomass ash will significantly improve soil physicochemical properties, namely moisture retention and pH buffering, thereby enhancing the agronomic performance of chili (*Capsicum annum*) without inducing severe salinity stress.

2. Methodology

2.1 Sample Collection and Preparation

The biomass ash was collected from two target sources and labelled as “Sample 1” and “Sample 2” in a manner that ensures it is representative of the batch.

1. Sampling New Ash (Top Layer): Samples were collected from the topmost layer of the ash heap, where the ash is likely fresh and has been recently deposited.

2. Sampling Old Ash (Middle Layer): Ash samples were collected from the middle layer of the heap, which has been there for a longer period and might have undergone some physical and chemical changes.
3. Sampling Very Old Ash (Bottom Layer): Ash was collected from the bottom layer of the heap, which may show significant weathering, compaction, and possibly some mineral transformations over time.

Composite Sampling:

After collecting individual sub-samples from different locations and depths of the heap (top, middle, and bottom), they were combined into one composite sample and mixed thoroughly in the collection container to achieve a homogeneous sample. The samples were labelled and stored in dry conditions until the tests were conducted. The target of collecting samples was to observe the physical and chemical parameters and conduct tests to check the applicability of use as a soil amendment.

2.2 Laboratory Characterization

2.2.1 pH Test

Soil pH is a critical parameter to test as the application of biomass ash (which is often alkaline) can alter the acidity or alkalinity of the soil, affecting nutrient availability and microbial activity. The soil pH was determined utilizing a soil-to-water suspension technique. First, a soil sample was mixed with distilled water at a 1:5 weight-to-volume ratio (20 g of soil to 100 ml of distilled water). The suspension was then stirred for several minutes and allowed to settle. Subsequently, the pH of the mixture was measured using a calibrated pH meter.

2.2.2 Electrical Conductivity (EC) Test

The electrical conductivity (EC) of the soil was determined utilizing a soil-to-water suspension technique. Initially, a soil sample was mixed with distilled water at a 1:5 weight-to-volume ratio (20 g of soil to 100 ml of distilled water). The suspension was stirred for several minutes and subsequently allowed to settle. Finally, the EC of the mixture was measured using a calibrated EC meter.

2.2.3 Density Test

To assess physical properties such as porosity and bulkiness, which influence soil aeration and water retention, a density test was conducted on the cinnamon leaf biomass ash. The density values of the ash samples were determined by first recording the mass of an empty beaker. Subsequently, a known volume (150 ml) of the ash sample was measured and transferred into the beaker.

2.2.4 Water Holding Capacity Test

Soil samples were collected from both the ash-treated test plots and the control plots for comparative analysis. A clean container was selected, and its empty mass was recorded. The container was then filled with a known mass of air-dried or moist soil, ensuring uniform packing. Distilled water was slowly added until the soil reached full saturation. Subsequently, the soil was allowed to drain freely for 1 - 2 hours to reach field capacity, representing the maximum water retained against gravity after macropore drainage. Following the drainage of excess water, the container and wet soil were weighed to determine the total wet mass. Finally, the amount of water retained in the soil was calculated utilizing the following formula:

$$WHC = \frac{m_3 - m_4}{m_4} \times 100$$

Where,

WHC = Water Holding Capacity

m₃ = Weight of the soil + water (after drainage)

m₄ = Weight of the soil before adding water (dry weight)

2.2.5 Field Test Methodology

Initially, the necessary materials and experimental containers were prepared. Ash samples were collected and homogeneously mixed with the soil according to the predetermined application ratios. To prevent waterlogging, small drainage holes were drilled at the base of each container. Subsequently, each container was clearly labeled according to its designated treatment group. To maintain optimal soil moisture for the plants, a consistent volume of water was manually applied to each unit. Throughout the subsequent growth period, plant development was systematically monitored, with growth parameters recorded weekly.

Selected Containers: Plastic cups (D = 7 cm, H = 8.5 cm, V = 180 ml).
Total number of containers: 4 Treatments × 5 Replicates = 20

Treatments:

1. Control: No ash application.
2. Low ash rate: 5 g ash per 1 kg soil equivalent.
3. Medium ash rate: 10 g ash per 1 kg soil equivalent.
4. High ash rate: 20 g ash per 1 kg soil equivalent.

A Uniform soil-ash mix was used for each treatment based on the specified ash rates.

Volume of a container = 180 ml
Soil weight in a container = 180 ml × 1.2 g/ml (soil density) = 216 g

Ash quantities for each treatment:

1. Low (5g/kg): 216 g soil × 5 g/kg = 1.08 g ash per container
2. Medium (10g/kg): 216 g soil × 10 g/kg = 2.16 g ash per container
3. High (20g/kg): 216 g soil × 20 g/kg = 4.32 g ash per container

Plant growth parameters, including height, leaf count, and other visible morphological changes, were measured and recorded weekly. Additionally, photographs of each experimental set were captured to visually document and compare these metrics.

3. Results and Discussion

This section analyzes and presents the results across three distinct subcategories. Additionally, observations from a preliminary survey of cinnamon oil refineries in Sri Lanka reveal a significant lack of proper waste management practices. Furthermore, most refinery owners possess limited awareness regarding the potential use of ash as an agricultural fertilizer. Discussions with refinery workers corroborated these findings, highlighting the absence of both established applications for the ash and formal waste management protocols during the extraction process. However, isolated instances were noted where ash has been informally applied as fertilizer to agricultural lands adjacent to the facilities.

3.1 Chemical and Physical Properties of Cinnamon Biomass Ash.

The chemical characterization results indicate that the biomass ash generated from cinnamon oil refinery processes is highly alkaline compared with typical agricultural soils. As shown in Table 1, the ash samples exhibited pH values between 11.85 and 12.28, significantly higher than the control soil pH of 7.92. Such high alkalinity is characteristic of biomass combustion residues due to the presence of alkaline oxides and carbonates of calcium, potassium, and magnesium formed during high-temperature combustion processes.

Table 1: Chemical Properties of Cinnamon Refinery Ash and Control Soil Sample

Sample Source	pH (1:5)	EC (mS/cm)
Sample A (Refinery: Horapawita)	12.28	28.10
Sample B (Refinery: Dampella)	11.85	24.85
Control Soil	7.92	0.12

As shown in Table 1, the strong alkalinity in the mix indicates that cinnamon ash has a high liming potential, suggesting that it may be particularly suitable for improving acidic soils such as the Red-Yellow Podzolic soils widely distributed in Sri Lanka. Similar alkaline characteristics have been reported for biomass ashes derived from wood and agricultural residues (Lamers et al., 2018; Voshell et al., 2018).

Furthermore, according to Table 1, ash also has relatively high electrical conductivity (24.85 – 28.10 mS/cm), indicating a high concentration of soluble salts. While these salts often contain beneficial plant nutrients such as potassium and calcium, excessive concentrations may increase soil salinity if the ash is applied in large quantities. Therefore, careful management of application rates is necessary when utilizing this material as a soil amendment.

Table 2: Density of the Samples

Sample Type	Sample Density
Sample 1 (Horapawita)	0.666 g/cm ³
Sample 2 (Dampella)	0.653 g/cm ³

In addition to its chemical properties, according to the table 2, the ash exhibited a low bulk density (average 0.66 g/cm³) compared with typical mineral soils. This low density reflects the porous structure of biomass ash particles and suggests that its incorporation into soil may improve soil aeration and reduce compaction. Improved soil porosity can enhance root penetration and water infiltration, contributing to better plant growth conditions.

3.2 Plant Growth Response and Salt Tolerance of *Capsicum annuum*

The pot experiment results demonstrated a clear positive relationship between biomass ash application and overall plant development. As detailed in Table 3, increasing the ash application rates consistently led to taller plants with larger leaf areas compared to the control group. This enhanced growth trajectory is visually corroborated in Figure 1, which captures the plants' progress at the end of the 14-week period.

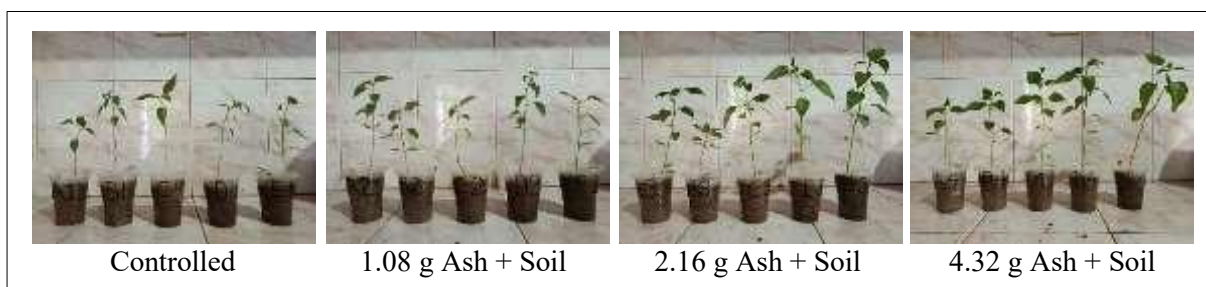


Figure 1: Field Test Plant Growth Progress After 14 Weeks

Despite the relatively high salinity and alkalinity of the raw ash, the chili plants (*Capsicum annuum*) exhibited strong growth responses. This observation can be partially explained by the moderate salt tolerance of chili plants. Many chili genotypes possess physiological mechanisms such as osmotic adjustment, ion compartmentalization, and selective ion uptake that allow them to tolerate moderate salinity levels without severe growth inhibition (Aktas et al., 2006). Furthermore, the buffering capacity of the sandy loam soil used in the experiment likely mitigated the initial chemical intensity of the ash.

Soil buffering processes can dilute soluble salts and moderate pH fluctuations, thereby reducing potential toxicity effects.

Table 3: Summary of Average Height, Average Leaf Area, and Average Number of Leaves

Set Number	Average Height (cm)	Average Number of Leaves	Average Leaf Area (cm ²)
Set 1: No ash application	11.1	5.4	4.00
Set 2: 1.08 g of ash + soil	11.2	6.4	8.82
Set 3: 2.16 g of ash + soil	15.0	7.4	11.65
Set 4: 4.32 g of ash + soil	16.0	7.8	11.87

As per the summary of the growth results shown in Table 3, the positive plant growth response observed in this study suggests that the nutrient benefits of the ash, particularly the supply of potassium and calcium commonly present in biomass ash, may outweigh the potential risks associated with salinity under controlled application conditions. In addition, improvements in soil physical properties, including enhanced aeration and moisture retention due to the low-density porous structure of ash particles, may have further contributed to the observed plant growth enhancement.

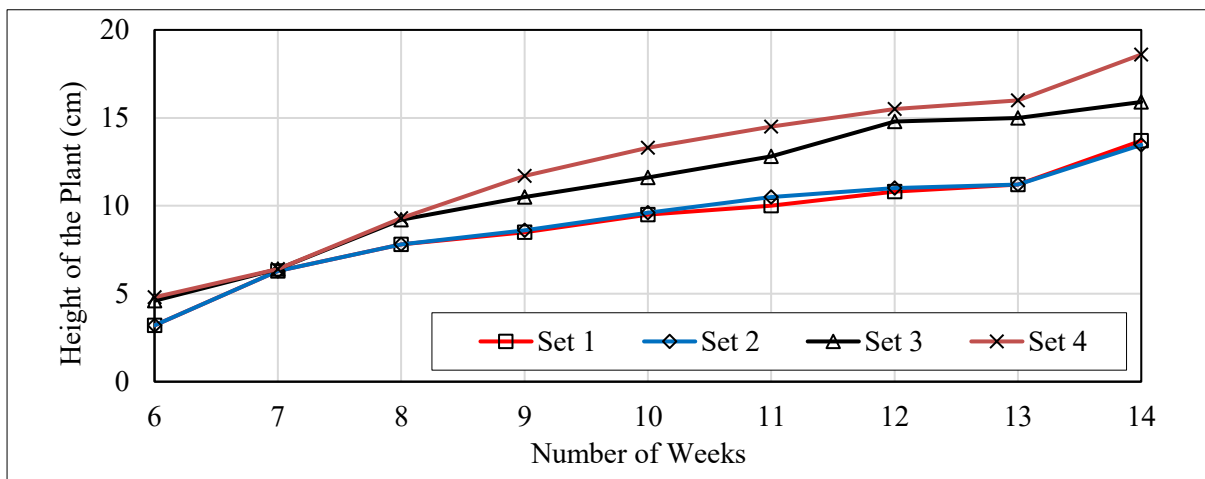


Figure 2: Plant Height Variation in Four Sets of Plants

Building on earlier observations, the addition of ash yielded considerable gains in plant height across the treated containers (Figure 2). This accelerated development extended to leaf area expansion; tracking over the 12th, 13th, and 14th weeks revealed a distinct upward trend strictly corresponding with the increased ash applications (Figure 3).

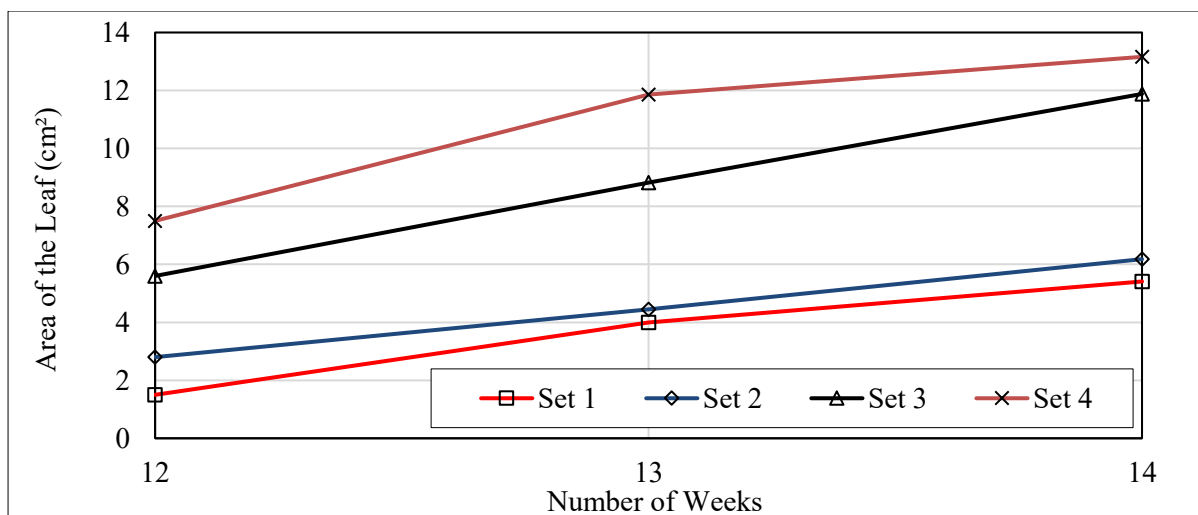


Figure 3: Leaf Area Variation in 12th, 13th, and 14th weeks

3.3 Water Holding Capacity Test

Table 4: Calculations for Water Holding Capacity

Sample Type	Dry Soil/Ash Weight	Wet Soil/Ash Weight	Water Holding Capacity (WHC)
Control Soil	164.22 g	215.835 g	31.43%
Sample 1 (Horapawita)	81.60 g	162.086 g	98.63%
Sample 2 (Dampella)	79.643 g	144.065 g	80.89%

According to Table 4, the water holding capacity values are higher when compared to those of the control soil. This means the ash sample can retain water, which is beneficial for plant growth.

The ash samples have a high percentage of water-holding capacity, indicating exceptionally high moisture retention compared to the soil. This is consistent with the literature, which reports that biomass ash typically has a low bulk density and high porosity, providing a large specific surface area and micro- and macropores that can retain substantial amounts of water. The porous structure and fine particles of biomass ash contribute to this enhanced water retention ability.

When mixed with soil, biomass ash could significantly improve the soil's water retention properties. This benefit is particularly valuable in tropical or arid environments (such as parts of Sri Lanka) where soil moisture conservation is crucial for crop growth and drought resilience. Improved WHC means plants could have better access to water between irrigation or rainfall events, potentially enhancing growth and yield.

Biomass ash can help improve soil aggregate formation due to the creation of a dual-pore system (micropores inside aggregates that hold water and macropores between aggregates that improve aeration). It can improve both water retention and soil aeration and root penetration.

Thus, as shown in Table 4, the soil WHC value of 31.43% is typical for many mineral soils but is quite low relative to the ash, suggesting that blending or amending soil with the ash could increase WHC substantially, based on the usage rate and mixing.

3.4 Comparative Analysis of Biomass Ashes

To place the results of this study within a broader context, the physicochemical characteristics of cinnamon refinery ash were compared with other commonly studied biomass ashes reported in the literature, and the summary is shown in Table 5.

Table 5: Comparative Characteristics of Selected Biomass Ashes

Ash Type	Typical pH	Key Characteristics	Reference
Cinnamon Ash	11.85 - 12.28	High alkalinity, high soluble salts, low density	Present Study
Rice Husk Ash	7.5 - 9.0	Very high silica ($\text{SiO}_2 > 80\%$), used for soil stabilization	Singh et al. (2008)
Wood Ash	9.0 - 11.0	Rich in calcium and potassium, commonly used as a soil amendment	Pugliese et al. (2014)
Straw Ash	10.0 - 11.5	High soluble potassium salts (KCl , K_2SO_4)	Zajac et al. (2018)
Coal Fly Ash	8.0 - 10.0	High alumina and iron content; potential heavy metal concerns	Basu et al. (2009)

Compared with other biomass ashes, cinnamon refinery ash demonstrates exceptionally high alkalinity, exceeding that of typical wood ash and rice husk ash. While rice husk ash is primarily valued for its high silica content and is widely used in soil stabilization and cementitious applications, cinnamon ash functions more effectively as a chemical soil amendment with liming potential. The relatively high electrical conductivity observed in cinnamon ash also resembles that of straw ash, which contains significant amounts of soluble potassium salts. These soluble minerals can contribute to plant nutrition when applied in appropriate quantities, but may lead to salinity stress if excessive amounts accumulate in the soil. From a resource management perspective, the findings highlight the potential of cinnamon biomass ash to be integrated into agricultural systems as a circular resource, transforming an industrial waste product into a value-added soil amendment. Such reuse strategies align with circular economy principles by reducing waste disposal while simultaneously improving soil fertility and agricultural productivity.

4. Conclusion

From the results and discussions, it can be concluded that there is considerable growth in plant height and leaf areas with the addition of ash, and a higher ash rate gives taller plants with larger and a greater number of leaves. However, there are considerable positive impacts and several limitations for the growth of plants, as discussed in Table 6. A comprehensive breakdown of the overall conclusions and parameter interpretations is provided in Table 7.

Table 6: Benefits and Limitations

Benefits	Limitations
Improves pH in acidic soils	High EC can harm sensitive plants
Enhance water retention and aeration	Over-application may lead to salinity or nutrient imbalance
Supports plant growth	Only tested and valid for chili plants. (Leading to future study area: impact of cinnamon ash on other plants)

Table 7: Overall Conclusion of the Observations

Aspect	Observation	Interpretation
Soil pH	Test results - 12.28 and 11.85, likely increased due to ash's alkalinity.	Improve growth in acidic soils, but a risk occurs in nutrient imbalance if the pH becomes too high.
Soil Salinity (EC)	Test results - 28.10, 24.85 mS/cm. Increased EC from ash.	Field results depict growth improvement, suggesting EC is within tolerable limits or mitigated by soil buffering.

Water Retention	Test results - 80.89%, 98.63% improved by Ash's high water-holding capacity.	Helps in better moisture availability, as it contributes to increased plant height and leaf area.
Soil Structure	Test results - 0.67, 0.65 g/cm ³ . Improved porosity from low density.	Enhances root growth and nutrient uptake, reflected in better plant development.
Plant Growth	Height and leaf area increased.	It indicates that biomass ash, despite high pH and EC, positively influences plant growth under testing conditions.

Future research must prioritize optimizing cinnamon biomass ash application rates across diverse soil typologies and crop species to maximize agronomic benefits, such as enhanced water retention, while mitigating the risks of salinity and nutrient lockout associated with its strong alkalinity and high electrical conductivity (EC). Longitudinal field studies spanning multiple growing seasons are essential to evaluate the sustained impacts on soil health, nutrient cycling, and microbial activity, complemented by comprehensive physicochemical profiling and rigorous heavy metal screening to prevent cumulative ecological toxicity. To broaden agricultural applicability, investigations should expand beyond chili (*Capsicum annuum*) to encompass a wider variety of crops, potentially incorporating ash pre-treatment techniques or prioritizing salt-tolerant varieties to manage the elevated EC. Finally, conducting comparative economic feasibility studies and comprehensive environmental impact assessments against synthetic fertilizers, alongside exploring alternative value-added applications like geotechnical soil stabilization or pH buffering in anaerobic digestion, will critically validate the role of this industrial byproduct within sustainable, circular bioeconomy frameworks.

References

- Aktas, H., Abak, K., & Cakmak, I. (2006). Genotypic variation in the response of pepper to salinity. *Scientia Horticulturae*, 110(3), 260-266. <https://doi.org/10.1016/j.scienta.2006.07.017>
- Albuquerque, A. R. L., Angelica, R. S., Merino, A., & Paz, S. P. A. (2021). Chemical and mineralogical characterization and potential use of ash from Amazonian biomasses as an agricultural fertilizer and for soil amendment. *Journal of Cleaner Production*, 298, 126472. <https://doi.org/10.1016/j.jclepro.2021.126472>
- Basu, M., Pande, M., Bhadoria, P. B. S., & Mahapatra, S. C. (2009). Potential fly-ash utilization in agriculture: A global review. *Progress in Natural Science*, 19(10), 1173-1186.
- Department of Cinnamon Development. (2024). Overview of the Cinnamon Industry and Oil Extraction. Ministry of Agriculture and Plantation Industries, Government of Sri Lanka. (Note: If you accessed this from their specific website, you can add "Retrieved from [URL]" at the end).
- Kowalska, J., Tyburski, J., Matysiak, K., Jakubowska, M., Lukaszuk, J., & Krzyminska, J. (2021). Cinnamon as a useful preventive substance for the care of human and plant health. *Molecules*, 26(17), 5299. <https://doi.org/10.3390/molecules26175299>
- Lamers, F., Cremers, M., Matschegg, D., Schmidi, C., Hannam, K., & Hazlett, P. (2018). Options for increased use of ash from biomass combustion and co-firing. *IEA Bioenergy*, Vol. 7, 7–51.
- Ohno, T., & Erich, M. S. (1990). Effect of wood ash application on soil pH and soil test nutrient levels. *Agriculture, Ecosystems & Environment*, 32(3-4), 223-239.
- Pugliese, S., Jones, T., Preston, M. D., Hazlett, P., Tran, H., & Basiliko, N. (2014). Wood ash as a forest soil amendment: The role of boiler and soil type on soil property response. *Canadian Journal of Soil Science*, 94(5), 621-634.
- Reijnders, L. (2004). Disposal, uses and treatments of combustion ashes: A review. *Resources, Conservation and Recycling*, 43(3), 313–336. <https://doi.org/10.1016/j.resconrec.2004.06.007>
- Risse, M., & Gaskin, J. (2016). Best Management Practices for Wood Ash as Agricultural Soil Amendment. University of Georgia Cooperative Extension, Bulletin 1142.
- Serafimova, E., Mladenov, M., Mihailova, I., & Pelovski, Y. (2011). Study on the characteristics of waste wood ash. *Journal of the University of Chemical Technology and Metallurgy*, 46(1), 31-34.
- Silva, F. C., Cruz, N. C., Tarelho, L. A. C., & Rodrigues, S. M. (2019). Use of biomass ash-based materials as soil fertilisers: Critical review of the existing regulatory framework. *Journal of Cleaner Production*, 214, 112–124.
- Singh, D., Kumar, R., Kumar, A., & Rai, K. N. (2008). Synthesis and characterization of rice husk silica, silica-carbon composite and H₃PO₄ activated silica. *Cerâmica*, 54(330), 203-212.
- Vassilev, S. V., Vassileva, C. G., Song, Y.-C., Li, W.-Y., & Feng, J. (2017). Ash contents and ash-forming elements of biomass and their significance for solid biofuel combustion. *Fuel*, 208, 377-409. <https://doi.org/10.1016/j.fuel.2017.07.036>
- Voshell, S., Mäkelä, M., & Dahl, O. (2018). A review of biomass ash properties towards treatment and recycling. *Renewable and Sustainable Energy Reviews*, 96, 479–486. <https://doi.org/10.1016/j.rser.2018.07.025>
- Zajac, G., Szyszlak-Barglowicz, J., Gołębowski, W., & Szczepanik, M. (2018). Chemical characteristics of biomass ashes. *Energies*, 11(11), 2885. <https://doi.org/10.3390/en11112885>

ICRES26_076

**PATH FROM AWARENESS TO BEHAVIOR IN THE ORGANIC FOOD MARKET:
A NEW MODEL FOR SUSTAINABILITY IN THE CONTEXT OF CIRCULAR
ECONOMY**

U.G.C. Lakchan^{1*}, G.C. Samaraweera², T.S.L.W. Gunawardana³, P.J.S. Fernando⁴

¹Faculty of Graduate Studies, University of Sri Jayawardenepura

²Faculty of Agriculture, University of Ruhuna

³Faculty of Management and Finance, University of Ruhuna

⁴Faculty of Management Studies and Commerce, University of Sri Jayawardenepura

**Correspondence E-mail: chamindalakshan1994@gmail.com, T.P: +94717510858*

Abstract: The current study investigates the effect of the awareness of Circular Economy principles that apply in the Organic food market on actual purchasing behaviour with mediators of attitude and purchase Intention with an aim of identifying the translation of consumer awareness on practical usage. Deductive approach and the Pragmatist research Philosophy was employed. Data were collected from 222 organic foods consumers in the Colombo District, Sri Lanka who normally purchase organic food products from supermarkets and organic foods stores. Multistage sampling was employed through the application of stratified random sampling, GPS-based random location selection, and systematic random sampling. Structural Equation Modelling (SEM) was employed to determine the suggested associations among the variables. The results validate path starting from Awareness to Behaviour emphasizing that consumer attitude and buying intention simultaneously mediate the relationship between the awareness and the actual consumption. Study has mainly limited to identify and minimize the awareness behaviour gap existing in CE and the organic foods Market and provides rich findings by contributing theoretically to extend the Theory of Planned Behaviour. Practically, the results guide policymakers and organizations to design interventions beyond awareness campaigns. Strategies should sequentially target attitude building and purchase intention through credible information, labelling and circular product design, enabling measurable behavioural change and effective implementation of circular economy practices. The findings highlight the societal importance of awareness-driven attitude formation in promoting sustainable consumption. By strengthening public understanding of circular economy principles, communities can foster pro-environmental norms, responsible lifestyles, and collective behavioural shifts supporting long-term social and environmental well-being thus enabling the achievement of SDG12, Sustainable Production and Consumption. The study introduces and validates a new model connecting awareness, attitudes, intentions, and actual consumption by extending TPB's starting point as Awareness. It enriches CE and consumer behaviour by providing suggestions for policy makers, marketers, and stakeholders by promoting organic foods consumption.

Keywords: Organic consciousness; Circular Economy; Ecological consumption; Intention to buy; Consumer behaviour

1. Introduction

The global sustainability movement has increasingly put more emphasis on organic food systems and Circular Economy (CE) models as pivotal ways toward responsible consumption and production (SDG 12). Nevertheless, the literature to date has largely addressed these frameworks in mutual isolation of one another, without taking into account the potential synergies that could be generated by merging them. Organic farming, characterized by chemical-free and natural production orientation (Reganold & Wachter, 2016), is effective in achieving environmental and health objectives at the production level but not at the post-consumption level. CE models, however, concentrate on material loop closure by reuse, recycling, and minimization of waste (Ellen MacArthur Foundation, 2015) but are less likely to direct attention to ecological and health benefits of organic inputs. This disconnection is an instant missing link in sustainability scholarship because every strategy in isolation fails to encompass the entire chain of sustainable consumption and production. This study bridges this gap by investigating how consumer knowledge of organic products, defined under CE discourse, affects buying habits. While earlier literature has discussed holistically organic consumption determinants (Yadav & Pathak, 2016) as well as barriers to CE adoption (Kirchherr et al., 2018), scant empirical work exists in their inter-link, particularly in developing economies like Sri Lanka. The Sri Lankan scenario is especially relevant with reference to its fledging organic retail industry (Wijesinghe et al., 2021) as well as country-level CE policy initiatives. Second, the awareness-behavior gap to sustainable consumption is an individual event preceding and being specifically different from the widely researched intention-behavior gap in literature (Malkanthi, 2021; Kapuge, 2016). While the intention-behaviour gap examines why intentions that have been formed aren't utilized (Osberghaus et al., 2025), the awareness-behavior gap is related to a preceding cognitive gap where consumers are aware of sustainability benefits but don't even form purchase intentions. It is this disconnection that is most clearly illustrated in organic consumer markets and the circular economy, where intense awareness repeatedly fails to generate underlying consumption habits. Current studies reflect this gap quite well. In organic shops, although 90% of shoppers rightly identify organic certification symbols (Organic Trade Association, 2023), just 31% claim to actually consider buying organic while shopping. Similarly, in circular economy strategies, 72% of shoppers identify recycling symbols and CE in general (European Commission, 2022), yet less than 18% choose products that apply CE principles when they shop. These patterns indicate an underlying consideration-knowledge gap prior to intention formation. The gap is a more critical issue than the intention-behavior gap since it occurs earlier in consumer engagement. The conventional theories like the Theory of Planned Behavior (Ajzen, 1991) have made the assumption that awareness would automatically translate into intention building and is not concerned about awareness but concerned with the attitude of the consumer, yet the awareness-behavior gap in the sustainable markets still refutes this assumption. Our study therefore introduces a novel conceptual model that cuts to this prior cognitive failure on how to convert passive awareness of sustainability into active consideration of purchase. By bridging this research gap, our research is able to contribute in three ways: (1) theoretical contribution by conceptualizing an integrated model that accentuates their synergies (Geissdoerfer et al., 2020); (2) empirical proof of the way CE-framed messaging enables organic market growth; and (3) policy implications for policymakers to enable organic and CE regimes contemporaneously. The figure outlines below depicts the overall picture of our study.

Research objectives of this study can therefore be formulated as;

Main Objective: To propose and validate a new model linking the awareness and actual purchasing behavior

- I. To examine the effect of the awareness of the principles of Circular Economy on consumer attitude.
- II. To identify the Impact of Consumer Attitude on Purchase Intention.
- III. To examine the Effect of Purchase Intention on Actual Purchase.
- IV. To examine whether the customer attitude work as a mediator between awareness and Intention.
- V. To examine whether the purchasing intention work as a mediator between attitude and Actual purchase.

2. Literature Review

The transition from linear production economies to circular economies is a paradigm shift in sustainable development with the goals of minimizing waste, proper use of resources, and system regeneration (Ellen MacArthur Foundation, 2019). This revolutionary design promotes closed-loop material flow that significantly minimizes the environment burden and maximizes economic value (Geissdoerfer et al., 2017). They cover widely when used in organic food systems to help achieve numerous of the Sustainable Development Goals (SDGs), such as SDG 3 (Good Health and Well-being) and SDG 12 (Responsible Consumption and Production) (United Nations, 2015). Organic production systems attain these results by eschewing synthetic inputs and leveraging ecosystem service delivery. Organic production systems achieve the above outcomes through the limitation of artificial inputs in the system. Empirical studies have shown that organic production systems promote ecological sustainability through the improvement of soil quality (Reganold & Wachter, 2016), biodiversity by 30% (Gomiero et al., 2011), as well as water retention. Furthermore, organic food systems have the advantage of lowering the costs of production for the farmer as well as the end consumer (SDG 3.9). Moreover, circular economy systems promote the development of strong urban food systems (SDG 12.2). New technologies in the field of organic waste fermentation and food sharing platforms have the potential to strengthen the above benefits. These technologies have the ability to contribute to the prevention of up to 19% of global diseases (Johns Hopkins Center for a Livable Future, 2023). Organic circular food systems thus play the role of an ecologically sustainable preventive health strategy. Hybridizing the circular economy with organic food systems is science-based options for the mitigation of other SDGs of serious global issues of public health and environmental sustainability.

2.1 Awareness of organic products adopting CE principles and attitude

This awareness among consumers acts as a major influencer of positive attitudes towards sustainable products, as environmental consciousness influences perceptions and judgments (Sharma & Foropon, 2019). Knowledge of the circular economy, specifically the 9R approach, influences positive attitudes towards sustainable products in various ways. Knowledge of the circular economy, such as the processes of resource regeneration, closed-loop supply chain management, and regenerative agriculture, influences perceptions of product efficiency, promoting ethical consumption (Gonella et al., 2024; Stern, 2000). Environmental consciousness has a positive effect on perceived behavioral control, as the idea of sustainable behavior becomes more palpable, which aligns with the Theory of Planned Behavior (Ajzen, 1991; Han, 2021). Research indicates that the more consumers are aware of the circular economy, the more positive their attitudes towards sustainable products become (Jimenez-Fernandez et al., 2023). Although only a small percentage of consumers have an idea of the circular economy, as opposed to the general awareness of recycling, there is a need to implement strategies to improve the general public's knowledge of the circular economy, which would further improve positive attitudes towards sustainable products

H1- Awareness of the principles of circular economy has a positive impact on consumer's attitude towards the behavior.

2.2 Consumer Attitude and Purchase Intention

Consumer attitude is an element of purchase intention, especially that of sustainable consumption and circular economy. The Theory of Planned Behavior (Ajzen, 1991) was used in various research studies to confirm the fact that health-consciousness attitude, greenness attitude, and product knowledge attitude have essential roles to play in influencing consumers' acceptability towards sustainable consumption practices (Sharma & Foropon, 2019). Strong international market correlations of purchasing intentions towards organic or green products with optimistic attitudes have been demonstrated. Attitudes of health and safety are the strongest motivators, which most frequently lead individuals to organic products, and environmental and ethical ones may make even a trend in behavior in this way concrete (Paul et al., 2020; Testa et al., 2021). Cross-cultural studies have repeatedly confirmed that attitudes based on a mix of moral, health, and safety issues occupy the key role of organic food purchasing intention (Paul et al., 2016; Testa et al., 2021). Local research also confirms these trends. Sri Lankan consumers primarily purchase organic food for health-related reasons, whereas in

India, both moral values and health awareness play significant roles in driving purchase intentions (Yadav & Pathak, 2016). Environmentalism and consumer safety orientation have a positive impact on attitude. A positive attitude is one that has a high level of purchase intentions for environmental products (Sharma & Foropon, 2019). Furthermore, the level of consumer education concerning the benefits of organic consumption has a positive impact on the level of purchasing intentions for consumers who are well-educated (Jimenez-Fernandez et al., 2023). This demonstrates the complex yet effective mechanisms through which attitudes operate.

H2- The attitude towards behavior has a positive impact on intention to purchase

2.3 Intention to Purchase and Actual Purchasing Behavior

Purchase intention is an excellent predictor of actual purchasing behavior. This is confirmed by the Theory of Planned Behavior proposed by Ajzen in 1991, indicating that purchase intention is mediated by attitudes, subjective norms, and perceived behavioral control (Fishbein & Ajzen, 1975). There is consistent evidence showing a positive link between purchase intention and sustainable consumption behavior (Carmona et al., 2023; Sembiring & Nisa, 2024). Green buying intention is found to strongly influence actual green purchasing behavior in different settings, including purchasing household appliances in South Africa (Dilotsotlhe, 2021) and other research on sustainable consumption behavior (Joshi & Rahman, as cited in Marvi et al., 2020; Frommeyer et al., 2022). Both the Theory of Reasoned Action and the Theory of Planned Behavior successfully explain the link between purchase intention and purchasing behavior, suggesting that a strong purchase intention is likely to significantly influence purchasing behavior (Nguyen et al., 2019; Verma & Chandra, 2017).

H3: The Intention to purchase has a positive impact on actual purchasing behavior.

2.4 Awareness, Attitude and Purchasing Intention

The link between consumer awareness, attitude and purchase intention has been explored extensively. Research evidence suggests that attitude is an important mediator between consumer awareness and purchase intention. Awareness is disseminated through information dissemination campaigns, advertising, branding, and other similar processes. Awareness influences consumer beliefs, which in turn affect consumer attitude and ultimately influence consumer purchase intention (Alqaysi et al., 2024; Rusdianto et al., 2022; Parashar, 2024). Unlike the general model of consumer purchase intention, where consumer attitude is shaped by product characteristics or brand-related factors, consumer attitude is shaped by product safety features or environmental protection aspects in the case of organic food purchase intention (Teixeira et al., 2021). The mediating effect of consumer attitude on consumer purchase intention is supported by the Theory of Planned Behavior (Ajzen, 1991) and the Hierarchy of Effects model (Lavidge & Steiner, 1961), which emphasize the significant effect of consumer attitude on consumer purchase intention.

H4: The Attitude towards the behavior work as a mediator between Awareness and Intention to Purchase.

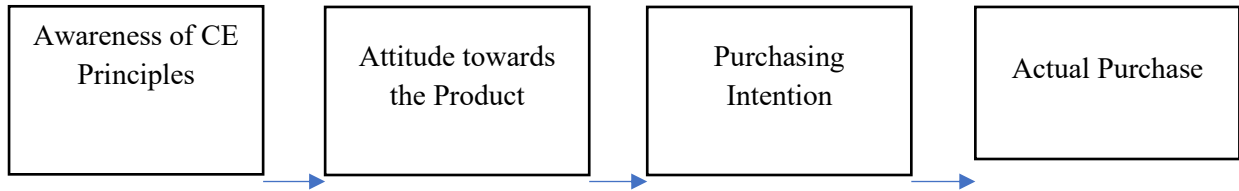
2.5 Mediating Role of Purchase Intention in the Relationship Between Attitude and Actual Purchase behavior

The relationship between consumer attitude and purchasing behavior has already been established with purchase intention as the key mediator between the two constructs. This is based on the Theory of Planned Behavior, which states that attitudes influence behavioral intentions and that these intentions are the driving force behind behavior (Ajzen, 1991). This means that intention is the key antecedent to behavior and the mediator between attitude and behavior. A series of research works conducted in different contexts, including green behavior, online shopping behavior, organic market behavior, among others, have shown that consumer attitude is positively related to purchase intention and purchase behavior (Yadav & Pathak, 2016). Literature has also shown that the attitude-behavior relationship is mediated by purchase intention (Moser, 2015; Lim et al., 2016). With the above literature in mind, the following hypothesis is proposed:

H5: Purchase intention is the mediator for the relationship between attitude and actual purchase behaviours.

3. Methodology

Conceptual Model of the Study



Source: Compiled by the Author

Figure 1: conceptual Model of the Study

The research methodology adopted in this study is a deductive approach based on pragmatism to ensure methodological flexibility in accomplishing the research objectives. A cross-sectional time horizon is employed in this study to assess the relationships between variables in a single time period. The sample size comprises 222 Sri Lankan organic consumers, and a structured questionnaire is employed to collect data from different selling venues and supermarkets in the Colombo Divisional Secretariat area. Data collection is carried out through a multistage random sampling approach, where initially stratified sampling is employed to segment the population based on relevant attributes, followed by a geographical approach through a GPS-based random sampling approach, and finally a systematic random sampling approach, where every alternate consumer is selected for this study.

Data collection is carried out through a survey approach using pre-tested scales to ensure the reliability and validity of the data collected in this study. Data analysis is carried out through a structural equation modeling approach using SmartPLS, where relationships between variables are modeled in this study. An SEM approach is employed in this study to examine relationships, test measurement constructs to ensure validity and reliability, and test structural models to test hypotheses, where both direct and indirect effects of exogenous variables on endogenous variables are evaluated in this study.

4. Results and Discussion

4.1 Descriptive Statistics

Table 1: Summary of Demographic Profile of Organic Consumers (n = 222)

Variable	Dominant Category	Percentage (%)
Age	31–40 years	50.45
Gender	Female	55.41
Education	Bachelor’s Degree	49.55
Income	Middle Class (LKR 50,001–150,000)	69.82
Residential Area	Sub-Urban	49.55
Ethnicity/Language	Sinhala	88.29
Employment	Full-time Employees	71.62
Household Size	3–4 Members	58.56

The demographic profile of 222 organic consumers in the Colombo District presents a mature and financially stable market segment. Half of the respondents (50.45%) belong to the 31-40 age group, which suggests that the organic food market is dominated by middle-aged consumers. Furthermore, the proportion of female consumers is slightly higher than that of their male counterparts (55.41%), which may indicate that consumers are slightly more inclined towards organic food shopping as females. The educational qualification of the consumers is also observed to have a strong impact on organic food shopping behavior, with almost half of the respondents (49.55%) possessing a Bachelor's qualification, which may indicate the positive correlation between educational qualifications and organic food shopping behavior. From the income distribution of the organic consumers, it is evident that the majority

(69.82%) belong to the middle-income group, followed by the upper middle group. Geographically, the majority of the consumers live in sub-urban (49.55%) and urban (42.79%) areas while the representation of the rural sector is very low (7.66%). The majority of the sample population speak the Sinhala language (88.29%), and the employment profile shows that full-time employees dominate the consumer segment (71.62%). Household size is medium-sized families of 3-4 persons, which dominate the sample population (58.56%). The results of this study have revealed that the majority of the organic food consumers in the Colombo District of Sri Lanka comprise an educated, middle-income, urban/sub-urban-dwelling, and professionally employed consumer segment of the population.

4.2 Measurement Model

This study aims to explore the relationships between consumer awareness, attitude, purchase intention, and behavior in the realm of sustainable and organic products. Previous studies have established that consumer attitude plays a vital role as a mediator between awareness and purchase intention. This implies that awareness influences consumer beliefs, which in turn generate positive or negative attitudes that influence their purchasing behavior (Ajzen, 1991; Pratama et al., 2023; Alqaysi et al., 2024). Purchase intention has been identified as one of the most powerful predictors of behavior. This intention encompasses motivational and decisional aspects that ultimately translate to concrete behavior (Fishbein & Ajzen, 1975; Sembiring & Nisa, 2024). Green and sustainable consumption behavior have been identified as a key driver of intention. Several studies have established the link between purchase intention and the manifestation of the same into concrete behavior (Marvi et al., 2020; Dilotsotlhe, 2021). This implies that while awareness plays a critical role, the attitude that follows awareness plays a critical role as the primary determinant of purchase intention.

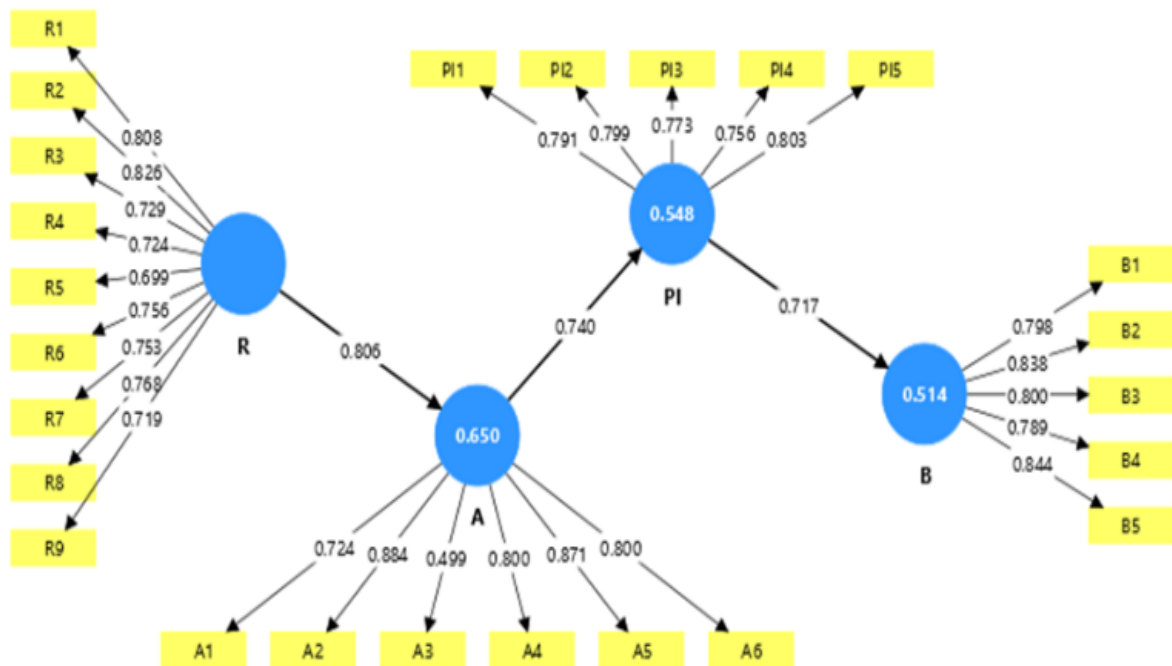


Figure 2: Measurement Model

Factor Loadings, Reliability, and Multicollinearity

Table 2: Factor Loadings, Reliability, and Multi-collinearity Assessment of Constructs

Source: compiled by the Author

Construct	Item	Factor Loading	Cronbach's Alpha	rho_A	rho_C	AVE	VIF	Decision
A	A1	0.724	0.861	0.893	0.897	0.599	1.875	Selected
	A2	0.884					3.130	Selected
	A3	0.499					1.431	Eliminated
	A4	0.800					2.143	Selected
	A5	0.871					2.700	Selected
	A6	0.800					2.229	Selected
B	B1	0.798	0.873	0.874	0.908	0.663	1.935	Selected
	B2	0.838					3.162	Selected
	B3	0.773					1.949	Selected
	B4	0.756					2.709	Selected
	B5	0.803					2.323	Selected
PI	PI1	0.791	0.846	0.853	0.889	0.616	1.919	Selected
	PI2	0.799					4.647	Selected
	PI3	0.798					2.020	Selected
	PI4	0.888					4.191	Selected
	PI5	0.806					2.156	Selected
R	R1	0.808	0.905	0.906	0.922	0.570	2.965	Selected
	R2	0.826					3.091	Selected
	R3	0.729					2.227	Selected
	R4	0.724					2.316	Selected
	R5	0.699					1.909	Near threshold
	R6	0.756					2.659	Selected
	R7	0.753					2.571	Selected
	R8	0.768					2.130	Selected
	R9	0.719					1.868	Selected

This table shows the factor analysis, reliability test, and multicollinearity test results for four different variables: Attitude (A), Behavior (B), Purchase Intention (PI), and Awareness of Circular Economy Principles (R) (Schmitt & Sass, 2011; Hair et al., 2010). Factor loading indicates the measurement of each variable in relation to its corresponding factor. In this study, it is found that A3 should be removed because it has a low factor loading (Schmitt & Sass, 2011). Reliability analysis results, such as Cronbach's Alpha and Composite Reliability rho_A and rho_C, show high reliability for all four constructs (Manterola et al., 2018). AVE results support convergent validity (Hair et al., 2010) while VIF results show no severe multicollinearity problems (Hair et al., 2010). Overall, all of these results are statistically significant and support the use of these constructs in analyzing consumer behavior towards sustainable products (Ajzen, 1991; Sharma and Foropon, 2019).

4.3 Structural Model

The empirical study applied structural equation modeling to test hypotheses and measure the relationships between constructs. The model describes the connection between unmeasured latent variables. In addition, the structural model defines how latent constructs drive changes in other latent constructs' values either directly or indirectly. The endogenous and exogenous variable correlation was determined by path coefficients, confidence intervals, model fit, and R2 statistics. Therefore, the structural model of the current study can be discussed as below. Based on the aforementioned model, resulting measures of model fit, path coefficients, confidence intervals, R2, and can be shown as like shown in Figure 02.

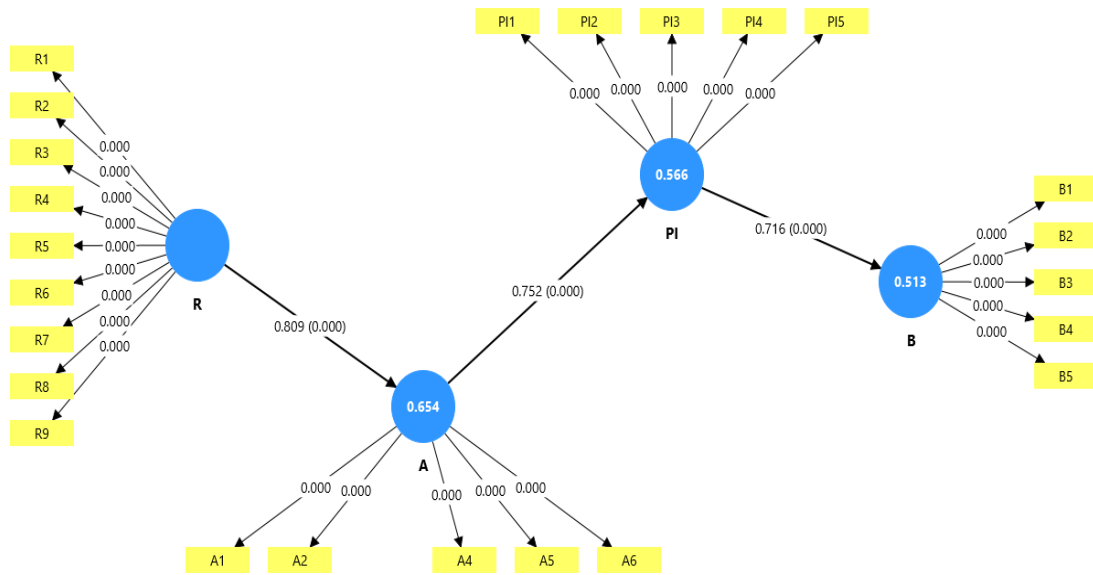


Figure 3: Structural Model

Table 3. Structural Model Fit Indices

Fit Index	Saturated Model	Estimated Model	Recommended Value
SRMR	0.101	0.119	< 0.10
d ULS	3.041	4.223	—
d G	3.099	3.264	—
Chi-square	1714.575	1786.632	—
NFI	0.535	0.516	≈ 0.90

Although the SRMR values slightly exceed the ideal threshold and NFI values are below conventional SEM benchmarks, such outcomes are acceptable in complex PLS-SEM models. Emphasis was therefore placed on predictive relevance and path significance, which were found to be strong and statistically robust. Overall, the findings support the proposed structural framework and confirm the presence of a significant two-stage mediation process linking CE Principles to sustainable behavioral outcomes.

Table 4. Summary of Structural Relationships

Type	Relationship	β	t-value	p-value	R ² (Endogenous Variable)
Direct	R → A	0.809	32.484	<0.001	0.654
Direct	A → PI	0.752	23.579	<0.001	0.566
Direct	PI → B	0.716	14.519	<0.001	0.513
Indirect	R → A → PI	0.609	8.399	<0.001	—
Indirect	A → PI → B	0.539	4.942	<0.001	—
Chain Mediation	R → A → PI → B	0.436	4.289	<0.001	—

The results indicate strong direct effects from CE Principles to Attitude, from Attitude to Purchase Intention, and from Purchase Intention to Behavior. Additionally, significant indirect and chain mediation effects confirm that sustainable behavior is influenced through sequential attitudinal and intentional mechanisms. The R² values demonstrate that the model explains 65.4% of Attitude, 56.6% of Purchase Intention, and 51.3% of Behavior.

4.4 Hypothesis Testing

Table 5: Hypothesis Testing

Hypothesis	Path	Original sample (O)	Sample mean (M)	Standard deviation (STDEV)	T statistics (O/STDEV)	P values	Supported or Not
H ₁	R -> A	0.809	0.812	0.025	32.484	0.000	Supported
H ₂	A -> PI	0.752	0.755	0.032	23.579	0.000	Supported
H ₃	PI -> B	0.716	0.720	0.049	14.519	0.000	Supported
H ₄	R -> A-> PI	0.609	0.614	0.037	16.584	0.000	Supported
H ₅	A-> PI -> B	0.539	0.545	0.057	9.522	0.000	Supported
Total Mediation path	R -> A-> PI -> B	0.436	0.443	0.052	8.376	0.000	Supported

Source: Survey Data (2025)

This study offers substantial empirical evidence in favor of a sequential model in which the level of awareness of circular economy concept (R) significantly impacts consumer attitude (A), and this attitude in turn significantly impacts purchase intention (PI) and, finally, purchase behavior (B). All these relationships were found to be statistically significant, thus validating the significance of attitude in influencing purchase behavior through indirect factors of attitude and purchase intention (Pratama et al., 2023; Kongarchapatara & Hanpanit, 2021; Vidal-Ayuso et al., 2023).

Theoretical Implications

This study extends the Theory of Planned Behavior by placing awareness as a key antecedent factor that triggers attitude. It emphasizes the key role played by attitude in shaping intention to purchase and actual purchasing behavior. The extension to the Health Belief Model reinforces the psychological process that links awareness to attitude and subsequently to intention to purchase and actual purchasing behavior.

Practical Implications

While awareness is a key driver in the process to purchasing behavior, it is not enough on its own to generate the desired purchasing behavior. It is therefore imperative that policymakers introduce a system of certification and labeling to raise awareness and build confidence among consumers. Similarly, it is essential that organizations adopt the circular economy model to enhance the sustainability of the organization as well as the product.

Limitations and Future Research

However, this research has some limitations, such as the consideration of only cognitive factors, the application of the quantitative method from the point of view of a single country, and the lack of a comprehensive analysis of systemic policy interventions. To expand this research, it is suggested that future research should be based on the consideration of strategies related to affective and emotional engagement, the application of the cross-cultural framework to verify the results, and the consideration of multi-level policy interventions to expand the research scope regarding the concept of the circular economy (Baah et al., 2021; Aljaber et al., 2021).

References:

- Ajzen, I. (1991). The theory of planned behavior. *Organizational Behavior and Human Decision Processes*, 50(2), 179–211. [https://doi.org/10.1016/0749-5978\(91\)90020-T](https://doi.org/10.1016/0749-5978(91)90020-T)
- AlJaber, A., Martinez-Vazquez, P., & Baniotopoulos, C. (2023). Barriers and Enablers to the Adoption of Circular Economy Concept in the Building Sector: A Systematic Literature Review. *Buildings*. <https://doi.org/10.3390/buildings13112778>.
- Alqaysi, S., Zahari, A., & Khudari, M. (2024). Awareness advertising influence on consumers buying intention: Exploring attitude as a mediating factor. *Journal of Infrastructure, Policy and Development*. <https://doi.org/10.24294/jipd.v8i7.4568>.
- Baah, C., Afum, E., Agyabeng-Mensah, Y., & Agyeman, D. (2021). Stakeholder Influence on Adoption of Circular Economy Principles: Measuring Implications for Satisfaction and Green Legitimacy. *Circular Economy and Sustainability*, 2, 91 - 111. <https://doi.org/10.1007/s43615-021-00093-2>.
- Ellen MacArthur Foundation. (2015). Growth within: A circular economy vision for a competitive Europe. <https://ellenmacarthurfoundation.org/growth-within-a-circular-economy-vision-for-a-competitive-europe>
- Ellen MacArthur Foundation. (2019). Completing the picture: How the circular economy tackles climate change. <https://ellenmacarthurfoundation.org/completing-the-picture>
- Food and Agriculture Organization (FAO). (2022). Organic agriculture and nutrient cycling. <http://www.fao.org/organicag>
- European Commission (EC). (2022). Eurobarometer on circular economy attitudes (Special Report 524). <https://europa.eu/eurobarometer/surveys/detail/2670>
- FAO. (2022). The State of the World's Land and Water Resources for Food and Agriculture: Systems at breaking point. Rome: Food and Agriculture Organization of the United Nations. <https://doi.org/10.4060/cb9910en>
- Fishbein, M., & Ajzen, I. (1975). Belief, attitude, intention, and behavior: An introduction to theory and research. Reading, MA: Addison-Wesley.
- Fobbe, L., & Hilletofth, P. (2022). Moving toward a circular economy in manufacturing organizations: the role of circular stakeholder engagement practices. *The International Journal of Logistics Management*, 34(3), 674–698. <https://doi.org/10.1108/ijlm-03-2022-0143>
- Geissdoerfer, M., Savaget, P., Bocken, N. M. P., & Hultink, E. J. (2017). The Circular Economy - A new sustainability paradigm? *Journal of Industrial Ecology*, 21(3), 603-614. <https://doi.org/10.1111/jiec.12603>
- Gomiero, T., Pimentel, D., & Paoletti, M. G. (2011). Environmental impact of different agricultural management practices: Conventional vs. organic agriculture. *Critical Reviews in Plant Sciences*, 30(1-2), 95-124. <https://doi.org/10.1080/07352689.2011.554355>
- Gonella, J. D. S. L., Godinho Filho, M., Ganga, G. M. D., Latan, H., & Jabour, C. J. C. (2024). A behavioral perspective on circular economy awareness: The moderating role of social influence and psychological barriers. *Journal of Cleaner Production*, 441, 141062. <https://doi.org/10.1016/j.jclepro.2024.141062>
- Han, F. (2021). The Relations between Teaching Strategies, Students' Engagement in Learning, and Teachers' Self-Concept. *Sustainability*, 13(9), 5020. <https://doi.org/10.3390/su13095020>
- Jimenez-Fernandez, A., Aramendia-Muneta, M. E., & Alzate, M. (2023). Consumers' awareness and attitudes in circular fashion. *Cleaner and Responsible Consumption*, 11, 100144. <https://doi.org/10.1016/j.clrc.2023.100144>
- Johns Hopkins Center for a Livable Future. (2023). Food system impacts on health and environment. Johns Hopkins Bloomberg School of Public Health.
- Kirchherr, J., Reike, D., & Hekkert, M. (2017). Conceptualizing the circular economy: An analysis of 114 definitions. *Resources, Conservation and Recycling*, 127, 221-232. <https://doi.org/10.1016/j.resconrec.2017.09.005>
- Kirchherr, J., Reike, D., & Hekkert, M. (2017). Conceptualizing the circular economy: An analysis of 114 definitions. *Resources, Conservation and Recycling*, 127, 221–232. <https://doi.org/10.1016/j.resconrec.2017.09.005>

- Kongarchapatara, B., & Hanpanit, S. (2021). Examining customers' intention to purchase circular economy products using Theory of Planned Behavior and moderating effects. *Academy of Strategic Management Journal*, 20(3), Article 778.
- Lavidge, R. J., & Steiner, G. A. (1961). A model for predictive measurements of advertising effectiveness. *Journal of Marketing*, 25(6), 59–62. <https://doi.org/10.1177/002224296102500611>
- Malkanathi, S. P. (2021). Outlook of present organic agriculture policies and future needs in Sri Lanka. *Zeszyty Naukowe SGGW W Warszawie - Problemy Rolnictwa Światowego*, 21(3), 55–72. <https://doi.org/10.22630/prs.2021.21.3.13>
- Organic Trade Association (OTA). (2023). U.S. organic industry survey 2023. <https://ota.com/resources/organic-industry-survey>
- Paiva, T. (2025). A Systematic Review of Driving Sustainability Through Circular Economy Marketing: Insights and Strategies for Green Marketing Innovation. *Encyclopedia*, 5(2), 61. <https://doi.org/10.3390/encyclopedia5020061>
- Parashar, S., Singh, S., & Sood, G. (2022). Examining the role of health consciousness, environmental awareness and intention on purchase of organic food: A moderated model of attitude. *Journal of Cleaner Production*. <https://doi.org/10.1016/j.jclepro.2022.135553>.
- Paul, J., Modi, A., & Patel, J. (2016). Predicting green product consumption. *Journal of Retailing and Consumer Services*, 29, 123-134. <https://doi.org/10.1016/j.jretconser.2015.11.006>
- Pratama, A., Hamidi, M., & Cahyono, E. (2023). The effect of halal brand awareness on purchase intention in indonesia: the mediating role of attitude. *Cogent Business & Management*, 10. <https://doi.org/10.1080/23311975.2023.2168510>.
- Reganold, J. P., & Wachter, J. M. (2016). Organic agriculture in the twenty-first century. *Nature Plants*, 2(2), 15221. <https://doi.org/10.1038/nplants.2015.221>
- Rusdianto, H., & Ummah, F. (2022). Brand Awareness, Halal Label, Subjective Norm Towards Purchase Intention Through Attitude as an Intervening Variable. *Journal of Economics and Public Health*. <https://doi.org/10.37287/jeph.v1i3.2266>.
- Sharma, A., & Foropon, C. (2019). Green product attributes in circular economy. *Management Decision*, 57(4), 1018-1042. <https://doi.org/10.1108/MD-10-2018-1092>
- Sheeran, P. (2002). Intention-behavior relations: A conceptual and empirical review. *European Review of Social Psychology*, 12(1), 1-36. <https://doi.org/10.1080/14792772143000003>
- Stern, P. C. (2000). Toward a coherent theory of environmentally significant behavior. *Journal of Social Issues*, 56(3), 407–424. <https://doi.org/10.1111/0022-4537.00175>
- Testa, F., Iraldo, F., Vaccari, A., & Ferrari, E. (2021). Why eco-labels can be effective marketing tools. *Business Strategy and the Environment*, 24(4), 252-265. <https://doi.org/10.1002/bse.1821>
- United Nations Environment Programme (UNEP). (2023). Food waste index report 2023. <https://www.unep.org/resources/report/unep-food-waste-index-report-2023>
- Vidal-Ayuso, F., Akhmedova, A., & Jaca, C. (2023). The circular economy and consumer behaviour: Literature review and research directions. *Journal of Cleaner Production*, 418, 137824. <https://doi.org/10.1016/j.jclepro.2023.137824>
- Wijesinghe, A., & Aththanayaka, W. (2021). Assessing Urban Consumer Intention on Purchasing of Organic Food in Sri Lanka. . <https://doi.org/10.4038/jas.v16i1.9185>.
- World Health Organization (WHO). (2022). Guidelines for drinking-water quality: Fourth edition incorporating the first and second addenda. <https://www.who.int/publications/i/item/9789240045064>
- Yadav, R., & Pathak, G. S. (2016). Intention to purchase organic food among young consumers: Evidences from a developing nation. *Journal of Cleaner Production*, *135*, 732-739. <https://doi.org/10.1016/j.jclepro.2016.06.120>
- Manterola, C., Quiroz, G., Salazar, P., & García, N. (2018). Methodology of research in surgery: Designs of observational studies. *International Journal of Morphology*, 36(1), 394–402. <https://doi.org/10.4067/S0717-95022018000100394>
- Dilotsotlhe, N. (2021). *The use of descriptive research design in social sciences research*. *International Journal of Research and Innovation in Social Science*, 5(6), 92–97.



ICRES

International Conference on
Resource Efficiency Towards Sustainability

**International Conference on
Resource Efficiency Towards Sustainability**

**SUSTAINABLE RESOURCE MANAGEMENT
AND URBAN DEVELOPMENT**



ICRES26_012

**THE IMPACT OF CONSUMER PREFERENCES ON THE SUSTAINABLE
DEVELOPMENT OF SRI LANKA'S HERBAL MEDICINE AGRO
INDUSTRY: LOCALLY SOURCED VS. IMPORTED PRODUCTS**

H.T.D.S. Karunarathna*, G.P. Maddumage

Aquinas College of Higher Studies, Sri Lanka

**Correspondence E-mail: deshasathsarani@gmail.com, TP: +94766477814*

Abstract: The consumption of herbal medicinal products is increasing rapidly nowadays due to consumer awareness of natural ingredients and perceived safety of herbal remedies compared to synthetic products. This study aims to identify not only the factors influencing consumer preferences but also their implications for the sustainable development of Sri Lanka's herbal agro industry by evaluating consumer preferences for local and imported herbal products. The data were collected from 272 respondents in Sri Lanka using the snowball sampling method and a questionnaire survey by employing a quantitative research design. Although previous studies in Sri Lanka's herbal medicinal sector have studied consumer preferences and sustainability separately, this study fills a significant research gap by integrating both factors. This research helps to develop effective strategies by explaining how consumer preferences affect social, economic and environmental sustainability. The results showed that sustainability was significantly influenced by perceived quality, cultural influence, brand trust and availability ($p < 0.001$). In addition, perceived quality and cultural influence have an indirect impact on sustainability through consumer preferences. According to the results, consumers who preferred locally sourced products showed higher commitment to sustainability ($P = 0.047$) than those who preferred imported products or were neutral. Gender and environmental consciousness were identified as significant moderating variables in the relationship between consumer preferences and sustainability. The results of this study provide valuable guidance for farmers, local producers and policymakers to improve local cultivation, production and plan effective marketing strategies. Aligning such strategies with consumer preferences can promote sustainable growth in Sri Lanka's herbal medicine agro industry. In addition, it also strengthens the competitiveness of local products in both domestic and international markets.

Keywords: Agro Industry; Consumer Preferences; Herbal Medicine; Locally Sourced Products; Sustainable Development,

1. Introduction

Medicinal products derived from plants that are used to treat health problems are known as herbal medicinal products. This study mainly focuses on the factors influencing consumer preferences for local herbal products and how they impact the sustainability in Sri Lanka. Local manufacturers need to have a deep understanding of the consumer preferences for local herbal medicinal products. It will help them survive in the market and compete with the imported brands. At the same time, it allows farmers, producers and policymakers to identify opportunities to expand the cultivation and production of herbal medicinal plants.

The global herbal medicine market has experienced rapid growth in recent years. In 2024, it was valued at about USD 214.32 billion and it is expected to increase to around USD 356.25 billion by 2029 with an annual growth rate of 10.9% (Herbal Medicine Market Report, 2025). In 2022, Sri Lanka generated about USD 36.34 million from the export of herbal medicinal products. The main export destinations included India, the Netherlands, the United States, Australia, the Czech Republic and the United Kingdom. Although Sri Lanka exports herbal medicinal products, its share of the global market is relatively small. However, it has good potential to expand the herbal medicinal sector due to its rich biodiversity and strong tradition of herbal knowledge. Although Sri Lanka has a wide variety of herbal plants, the country still heavily imports herbal medicinal products. In 2022, Sri Lanka imported herbal products worth around USD 5.85 million. (Bicost IX) 23rd & 24th, 2023).

Even with this potential, the cultivation and production of the herbal medicinal plants in Sri Lanka remain at a relatively limited level. It affects the local farmers and producers in meeting the market demand. Also, the lack of utilization of the country's rich biodiversity and traditional knowledge affects the ability to meet market demand.

Despite Sri Lanka heavily depending on imports of herbal medicinal products and exporting a significant amount of products, the existing research has not explored the relationship between consumer preferences and sustainable development in the herbal medicine agro industry. Previous studies have examined the consumer preferences for herbal products in a general way or have focused on sustainability separately. However, there is still a significant gap in understanding how consumer preferences for locally sourced products versus imported herbal products affect the three aspects of sustainability (Environmental, social and economic) in Sri Lanka. Moreover, there is limited research on the main factors that influence consumer preferences in Sri Lanka's herbal medicine market and how these preferences can be used to support local production and promote sustainable development.

This study's findings will guide local manufacturers and authorities in identifying key factors that affect consumer preferences for local herbal medicinal products. It will help them to make effective marketing strategies, develop products accordingly, contribute to the export sector and reduce imports. Also, Farmers can highly contribute to the cultivation of herbal medicinal plants. Accordingly, getting these actions can contribute to the social, economic and environmental sustainability in Sri Lanka. Additionally, this study helps to provide recommendations for promoting locally sourced herbal products based on consumer insights.

2. Methodology

2.1 Study Design

A quantitative study was conducted across all provinces of Sri Lanka, including rural, semi-urban, and urban areas, to obtain a more representative sample. The target population comprised current and potential consumers of herbal medicinal products because their preferences, habits, and expectations directly influence product success, market performance and sustainability outcomes. Since there is no defined list of herbal medicinal product users in Sri Lanka, the snowball sampling method was used to collect data from 272 respondents, through a standardized, structured questionnaire using five point likert scale ranging from strongly disagree to strongly agree. The questionnaire was developed based on the factors under the variables of the conceptual framework. About 4 to 7 questions were included under each factor of the questionnaire to obtain accurate responses. Before distributing the

questionnaire, a pilot test was conducted with a small group of respondents to ensure clarity and reliability of the questions. Descriptive statistics, multiple linear regression, and one-way ANOVA were employed to analyze the data using SPSS software.

2.2 Conceptual Framework

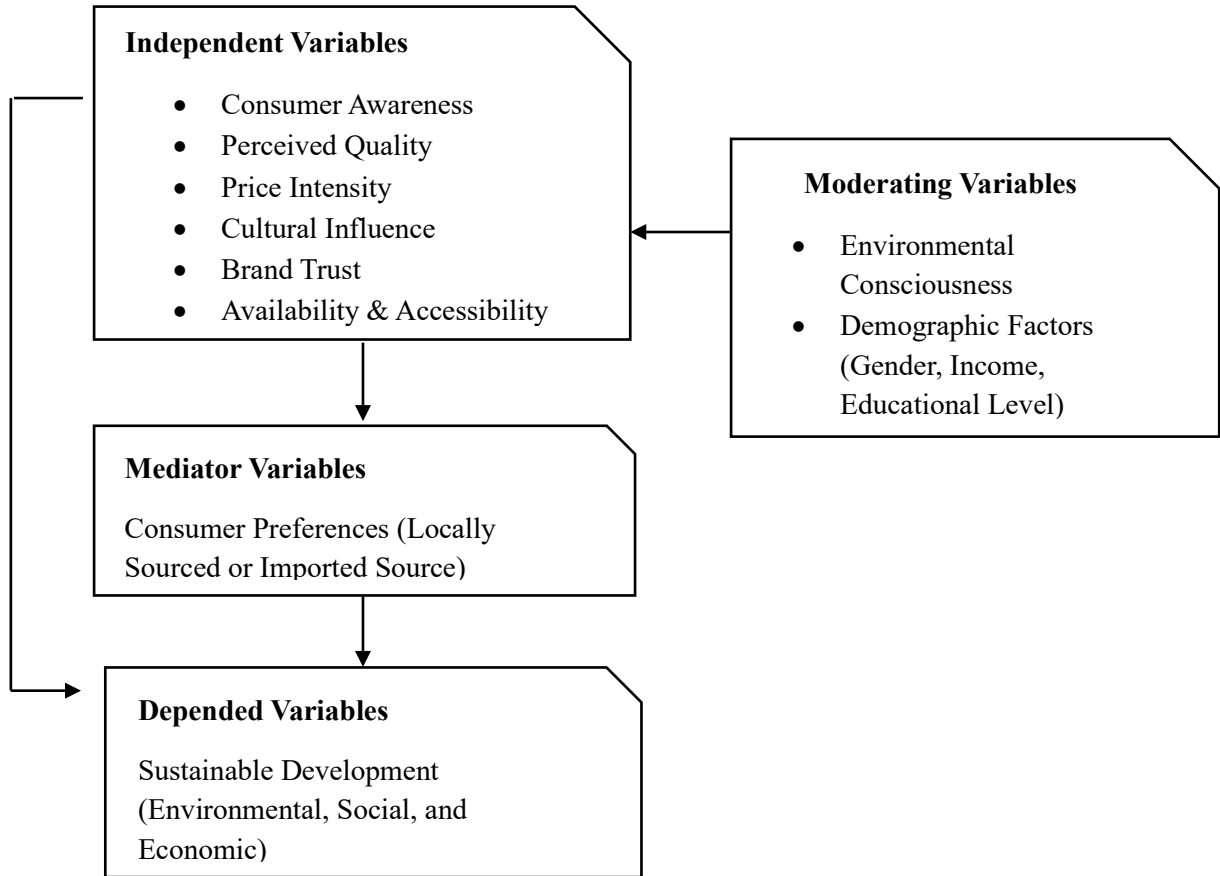


Figure 1: Conceptual Framework (adapted from Jokar et al., 2017; Smith-Hall and Hall, 2012; Suriyage, 2022; Tam and Baharun, 2019; Widyaningtyas, 2018)

2.3 Analytical Framework

This analytical framework includes three models of analysis. The first model examines the direct impact of the independent variables on sustainability which is considered the dependent variable. The second model analyzes how the independent variable influences consumer preferences which act as a mediating variable in the conceptual framework. Finally, the third model examines the overall effect on sustainability by including both the mediator and the independent variables as predictors.

The following regressions were utilized for this analysis.

$$\text{Regression 1: } S = \beta_0 + \beta_1 \cdot CA + \beta_2 \cdot PQ + \beta_3 \cdot PI + \beta_4 \cdot CI + \beta_5 \cdot BT + \beta_6 \cdot AA + \epsilon_1 \quad (1)$$

$$\text{Regression 2: } CP = \beta_0 + \beta_1 \cdot CA + \beta_2 \cdot PQ + \beta_3 \cdot PI + \beta_4 \cdot CI + \beta_5 \cdot BT + \beta_6 \cdot AA + \epsilon_1 \quad (2)$$

$$\text{Regression 3: } S = \beta_0 + \beta_1 \cdot CA + \beta_2 \cdot PQ + \beta_3 \cdot PI + \beta_4 \cdot CI + \beta_5 \cdot BT + \beta_6 \cdot AA + \beta_7 \cdot CP + \epsilon_1 \quad (3)$$

Where, CP = Consumer Preferences, CA = Consumer Awareness, PQ = Perceived Quality, PI = Price Intensity, CI = Cultural Influence, BT = Brand Trust, AA = Availability and Accessibility, β_0 = Intercept, $\beta_1 - \beta_7$ = Regression Coefficient and ϵ_1 = Error Term

To analyze moderating variables that impact sustainability, the following regression equations are used.

$$\text{Sustainability} = \beta_0 + \beta_1(\text{Consumer Preferences}) + \beta_2(\text{Gender}) + \beta_3(\text{Consumer Preferences} \times \text{Gender}) + \varepsilon \quad (4)$$

$$\text{Sustainability} = \beta_0 + \beta_1 (\text{Consumer Preferences}) + \beta_2 (\text{Environmental Consciousness}) + \beta_3 (\text{Consumer Preferences} \times \text{Environmental Consciousness}) + \varepsilon \quad (5)$$

$$\text{Sustainability} = \beta_0 + \beta_1 (\text{Consumer Preferences}) + \beta_2 (\text{Education}) + \beta_3 (\text{Consumer Preferences} \times \text{Education}) + \varepsilon \quad (6)$$

$$\text{Sustainability} = \beta_0 + \beta_1 (\text{Consumer Preferences}) + \beta_2 (\text{Income}) + \beta_3 (\text{Consumer Preferences} \times \text{Income}) + \varepsilon \quad (7)$$

Where, β_0 = Intercept, $\beta_1 - \beta_3$ = Regression Coefficient, ε = Error Term

3. Results and Discussion

3.1 Demographic profile of the sample

The majority of respondents were female (53.3%). 46.9% of respondents were males. 45.8% of respondents are in semi urban areas. The age range between 18-24 years (42.5%) was recorded as the majority in the survey. It may indicate that younger consumers are more interested in herbal medicinal products or are more active in online surveys. Only 1.8% of respondents were in the age of 65 years above. 41.5% respondents were employed. At the same time, the majority of consumers of herbal products have a bachelor's degree, accounting for 52%. That indicates educated consumers are more aware of herbal medicinal products and sustainability in this sector. Only 2.2% of respondents have a primary education.

Table 1: Demographic Profile

Factors		Frequency	Percentage %
Gender	Female	145	53.3
	Male	127	46.7
Place of Residence	Rural	60	21.8
	Semi Urban	126	45.8
	Urban	76	27.6
Distribution of Age	18-24	117	42.5
	25-34	88	32.0
	35-44	22	8.0
	45-54	14	5.1
	55-64	6	2.2
	>65	5	1.8
Income Level	<30,000 LKR	100	36.4
	30,000–50,000 LKR	56	20.4
	50,000–100,000 LKR	69	25.1
	Above 100,000 LKR	29	10.5
Employment Status	Student	111	40.4
	Employed	114	41.5
	Self-employed	31	11.3
	Unemployed	8	2.9
	Retired	4	1.5
Education Level	Primary	6	2.2

Secondary	50	18.2
Diploma/Certificate	51	18.5
Bachelor's	143	52.0
Postgraduate	18	6.5

3.2 Direct impact of independent variables on Sustainability

The regression analysis examining the direct impact, where Sustainability was the dependent variable and consumer awareness, perceived quality, price intensity, cultural influence, brand trust and availability and accessibility are the independent variables, the results (Table 2) revealed that Perceived Quality ($\beta = 0.213$, $p < 0.001$), Cultural Influence ($\beta = 0.197$, $p < 0.001$), Brand Trust ($\beta = 0.347$, $p < 0.001$), and Availability & Accessibility ($\beta = 0.202$, $p < 0.001$) significantly influenced sustainability. Perceived quality significantly influences sustainability because consumers are more likely to consume products that are safe, effective and reliable. Consumers always think about the ingredients, manufacturing standards and effectiveness before purchasing the herbal medicinal products because those products affect their health. When they clarify that those products in good quality, they purchase products frequently and stay loyal to those products. As a result of that, manufacturers always try to use high quality raw materials and produce high quality products. So, perceived quality support long term sustainability of the herbal medicinal agro industry. Then, the cultural influence significantly affects sustainability because Sri Lanka has a deep connection with the Ayurvedic practices and traditional knowledge. Many consumers trust herbal medicinal products because they believe in the traditional healing methods and traditional knowledge. This cultural attachment always engages consumers to purchase local herbal medicinal products. It helps to protect traditional knowledge and support local herbal plant cultivation. Therefore, cultural influence contributes to social and economic sustainability in this sector. Also, brand trust significantly affects the sustainability because consumers tend to choose products from brands that has good position in the market and are trustworthy. When consumers trust a brand, they keep purchasing its products and recommend them to others. This long term trust of the brand supports manufacturers to maintain stable demand, quality and a good production line. Therefore, building brand trust can enhance the sustainability of this sector. Availability and Accessibility play an important role in sustainability. Consumers are more likely to purchase herbal products that are easily available in the market. If herbal medicinal products are widely distributed through supermarkets, pharmacies and online platforms, consumers can easily obtain them when needed. So, easy access improves product usage and supports continuous market demand. This steady demand benefits manufacturers, farmers and distributors actively involved in the herbal medicinal product supply chain. Therefore, improving the availability and accessibility of herbal medicinal products can enhance economic sustainability.

Additionally, consumer awareness and price sensitivity were failed to find a significant impact on sustainability. Although consumers have general awareness about the local and imported herbal products, awareness alone does not affect sustainable purchasing behaviour. Similarly, price intensity was not a major determinant of sustainability. Because when consumers purchase herbal medicinal products, they consider the quality, effectiveness and trustworthiness of products even if the price is relatively higher.

Table 2: Direct Impact on Sustainability

Model	Coefficients ^a			t	Sig.
	Unstandardized Coefficients		Standardized Coefficients		
	B	Std. Error	Beta		
1 (Constant)	0.058	0.133		0.434	0.664

Consumer Awareness	0.025	0.051	0.026	0.48	0.632
Perceived Quality	0.213	0.053	0.205	3.996	0.000
Price Intensity	0.067	0.054	0.059	1.245	0.214
Cultural Influence	0.197	0.051	0.197	3.86	0.000
Brand Trust	0.347	0.056	0.335	6.159	0.000
Availability and Accessibility	0.202	0.056	0.176	3.616	0.000

a. Dependent Variable: Average of the sustainability variables

3.3 Impact on Consumer Preferences (Mediator Variable)

The analysis of predictors on consumer preferences (mediator variable), indicates that Perceived Quality ($\beta = 0.405$, $p < 0.001$) and Cultural Influence ($\beta = 0.191$, $p < 0.01$) significantly influence whether consumers prefer locally sourced or imported herbal products. The results revealed that consumers prefer high quality and the products related to their cultural values. Consumer awareness, price intensity, brand trust and availability and accessibility were not significant. This implies that consumers' preference formation is largely guided by product quality and alignment with cultural values rather than by awareness campaigns or price considerations.

Table 3: Impact on Consumer Preferences (Mediator Variable)

Model	Coefficients				
	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
(Constant)	0.635	0.167		3.81	0.000
Consumer Awareness	0.096	0.064	0.106	1.502	0.134
Perceived Quality	0.405	0.067	0.411	6.045	0.000
1 Price Intensity	-0.057	0.067	-0.053	-0.861	0.390
Cultural Influence	0.191	0.064	0.201	3.005	0.003
Brand Trust	0.092	0.07	0.093	1.309	0.192
Availability and Accessibility	0.093	0.069	0.086	1.347	0.179

a. Dependent Variable: Consumer Preferences

3.4 Indirect impact and Total impact on Sustainability

When considering the total effect on sustainability, including the consumer preferences as the mediating variable, the results (Table 4) indicate that consumer preferences itself became a significant predictor of sustainability ($\beta = 0.197$, $p < 0.001$), confirming a mediating role. When this mediator was added, the direct coefficients of some predictors, particularly Perceived Quality and Cultural Influence, decreased slightly but remained significant, indicating partial mediation. Therefore, perceived quality and cultural influence impact on sustainability directly and indirectly, by shaping consumer preferences.

Table 4: Total Impact on Sustainability

Model	Coefficients ^a					
	Unstandardized Coefficients		Standardized Coefficients	t	Sig.	
	B	Std. Error	Beta			
	(Constant)	-0.049	0.134		-0.363	0.717
	Consumer Awareness	0.005	0.05	0.005	0.093	0.926
	Perceived Quality	0.14	0.056	0.136	2.502	0.013
	Price Intensity	0.077	0.052	0.068	1.474	0.142
1	Cultural Influence	0.158	0.051	0.158	3.12	0.002
	Brand Trust	0.324	0.055	0.313	5.879	0.000
	Availability and Accessibility	0.18	0.055	0.157	3.305	0.001
	Consumer Preferences	0.197	0.049	0.188	4.014	0.000

a. Dependent Variable: Average of the sustainability variables

3.5 Indirect Effect (Mediation) Calculation

Indirect effect calculations (Table 5) shows that how certain factors, like perceived quality and cultural influence partially influence the consumer preferences, and it relates to sustainability. The strongest indirect pathway is from perceived quality to consumer preferences, which then leads to sustainability. The next strongest pathway is from cultural influence to consumer preferences and then to sustainability. Brand trust and availability directly affect sustainability. However, consumer awareness and price intensity do not have a significant impact.

Table 5: Indirect Effect (Mediation) Calculation = (β of (Independent Variables \rightarrow Consumer Preference) \times (Consumer Preference \rightarrow Sustainability))

Independent Variable	β (IV \rightarrow CP)	β (CP \rightarrow S)	Indirect Effect ($\beta \times \beta$)	Significant Trend
CA	0.096	0.197	0.0189	Weak, not significant (since $p > 0.05$ in Table 03)
PQ	0.405	0.197	0.0798	Strong, meaningful indirect effect
PI	-0.057	0.197	-0.0112	Negligible
CI	0.191	0.197	0.0376	Moderate indirect effect
BT	0.092	0.197	0.0181	Weak
AA	0.093	0.197	0.0183	Weak

3.6 Moderating Analysis

Results of moderating analysis (Table 6) revealed that Gender ($\beta = 0.104$, $p < 0.040$) and Environmental Consciousness ($\beta = -0.256$, $p < 0.007$) moderators showed a significant effect on sustainability.

Table 6: Moderating Analysis Results

Model	Standardized Coefficients	
	Beta	Sig.
Gender	0.104	0.040
Environmental Consciousness	-0.256	0.007

3. 7 Comparison: Locally Sourced vs. Imported Products

The one-way ANOVA (Table 7) was conducted to compare three groups. (Those who prefer local products, those who prefer imported products, and those who are neutral) According to the results, Consumers who prefer locally sourced herbal products ($p < 0.047$) showed greater commitment to sustainability could be identified.

Table 7: Impact of Sustainability of Local Vs. Imported One-way ANOVA

Comparison	Mean Difference	Sig.	Interpretation
Local vs. Imported	.42588	0.047	Local group shows higher sustainability
Local vs. Neutral	.05669	0.912	Lower sustainability
Imported vs. Neutral	-.36919	0.089	Marginal difference

One-way ANOVA reveals significant differences in Sustainability based on product preference (Sig. = .032).

The findings indicate that both product specific factors, such as quality, trust, accessibility and consumer driven factors such as preferences influenced by quality and cultural relevance play crucial roles in advancing Sustainability of the herbal medicine agro industry in Sri Lanka. According to the results of this study, Consumer Awareness and Price Intensity did not show a significant effect on sustainability. But among all factors studied, brand trust showed the strongest effect on sustainability. It indicated that when consumers believe that a brand is reliable, credible and trustworthy, they will support the products that contribute to sustainability. Therefore, building trust in local herbal medicinal brands among consumers is essential. The mediating role of consumer preferences showed that sustainability efforts succeed more when they are aligned with consumer values and choices. Furthermore, using locally sourced materials offers clear advantage compared to imports. This means that focusing on domestic supply chains in policy and marketing can strengthen the industry's sustainability efforts.

These findings significantly help policymakers and industry stakeholders in Sri Lanka. They can identify the main factors that should be improved to enhance the growth of the herbal medicinal sector. Government authorities should implement policies that encourage the development of high quality herbal products. This could include implementing the certification procedures and standardization of products. Additionally, providing financial support for farmers is a must. By providing subsidies and low interest loans to farmers, the government and private sector can improve the cultivation of raw materials. It can help reduce dependence on the imported raw material. At the same time, increasing the awareness of farmers about this opportunity is essential. Most local farmers do not have a better idea about the cultivation of herbal medicinal plants, especially women. Women can highly contribute to the cultivation of herbal medicinal plants by cultivating them in their home gardens. Implementing awareness programs about herbal plants that have higher market value, and new technologies are essential. Also, promoting research and developing the herbal medicinal sector should be done. It can lead to opening new opportunities to improve technologies, strengthening the value chain, reducing post harvest losses and understanding consumer behavior and market demand. Farmers, manufacturers, researchers, and policymakers should work together to implement best practices, knowledge exchange, market linkage and improve competitiveness in the local and international market. These strategies not only support economic growth but also enhance social, economic and environmental sustainability in the herbal medicinal agro industry in Sri Lanka.

Finally, demographic factors such as age, income, educational level and environmental awareness are very important because they can influence the effectiveness of consumer preferences lead to sustainable

outcomes. Overall, promoting high quality, culturally aligned, and locally sourced herbal products is a viable strategy to strengthen the sustainability of Sri Lanka's herbal medicine agroindustry determining the factors that affect consumer preference for herbal medicinal products, and investigating whether consumer preference serves as a mediator, which moderating factors act as the moderators and confirmed local product preferred group highly contribute to the sustainable growth of herbal medicine agro industry in Sri Lanka.

4. Conclusion

Understanding the determinants of consumer preference for herbal medicinal products is essential for the development of sustainable development of Sri Lanka. Local producers, farmers and authorities can use the findings of this study to build their products according to consumer preferences, create effective marketing strategies, contribute to the herbal medicinal plant cultivations and build proper policies related to the industry.

The findings indicate that perceived quality, cultural influence, brand trust and availability and accessibility have an indirect impact to the sustainability. Perceived quality and cultural influence indirectly affect sustainability as well through consumer preferences. Additionally, gender and environmental consciousness moderate how preferences affect the sustainability herbal medicine agro industry in Sri Lanka.

Based on these findings, local producers should improve product quality since perceived quality drives consumer preferences and sustainability and integrate traditional knowledge and cultural characteristics into product branding to boost consumer trust and emotional connection due to cultural influence directly affecting the sustainability. Since brand trust directly affects to the sustainability, producers should build their loyal customer base by allowing customers to participate in workshops, earn rewards and engage with local farmers. When customers feel a genuine connection with the brand, their likelihood of maintaining loyalty increases significantly. Also, expanding the distribution of products is needed in all provinces in Sri Lanka because availability and accessibility affect sustainability in a direct way as well. Adjust marketing strategies should be applied to attract different groups of consumers based on their education, gender, and concern for the environment. Furthermore, provide financial support and technical training to encourage commercial scale cultivation and reduce reliance on imports. So, these strategies significantly contribute to the environmental, economic, and social sustainable growth in Sri Lanka.

References

- And, R. (2025). Herbal Medicine Market Report 2025 - Research and Markets. [online] Researchandmarkets.com. Available at:
<https://www.researchandmarkets.com/reports/5939866/herbal-medicine-market-report>.
- NUTRACEUTICALS AND LEAD MEDICINAL COMPOUNDS FROM SRI LANKAN BIO RESOURCES 9th Sri Lanka Biennial Conference on Science and Technology (BICOST IX) 23rd & 24th. (2023). Available at:
https://www.nastec.gov.lk/files/bicost_reports/BICOST_IX/nutraceuticals_and_lead_medical_compounds_derived_from_sri_lankan_bio_resources.pdf.
- Jokar, N.K. et al. (2017) 'Consumers' acceptance of medicinal herbs: An application of the technology acceptance model', *Journal of Ethnopharmacology*, 209, pp. 197-206.
- Smith-Hall, C. and Hall, J.A. (2012) 'People, plants and health: A conceptual framework for understanding medicinal plant consumption dynamics', *Journal of Ethnobiology and Ethnomedicine*, 8(1), p. 34.
- Suriyage, R.D.S.D. and Leon, S.A.J. (2023). Factors Influencing Consumer Buying Decision towards Herbal Products in Monaragala District, Sri Lanka. *Kelaniya Journal of Management*, 12(1), p.55. doi:<https://doi.org/10.4038/kjm.v12i1.7739>.
- Tam, A.Y.L. and Baharun, R. (2019) 'Consumer perceived value in understanding herbal medicine consumption: A conceptual model', *Journal of Business and Social Review in Emerging Economies*, 5(1), pp. 9-18.
- Widyaningtyas, D. (2018) 'The conceptual model of consumer purchase intentions to herbal products', *Proceedings of ICTSS 2018*.

ICRES26_013

**SOCIO-ECONOMIC IMPLICATIONS OF FAST-FOOD CONSUMPTION IN
URBAN SRI LANKAN CONTEXT: EVIDENCE FROM WATTALA–MABOLA
URBAN COUNCIL AREA****M.A.F. Mubashshira*, K. Rewathy***Department of Geography, Faculty of Arts, University of Colombo***Correspondence E-mail: mubashshira314@gmail.com, TP: +94761788905*

Abstract: Fast food has become increasingly embedded in urban lifestyles, reshaping dietary behaviour, cultural practices, and household economics. The main objective of the research was to analyse the socio-economic impacts of fast-food consumption among urban dwellers. A mixed-method approach was used, considering on both primary and secondary data. The core dataset consisted of structured questionnaires administered to 116 residents selected through stratified sampling while considering the representation of all major ethnic groups in the study area. To conduct interviews, 20 purposively selected participants, including health officers, government officials, and community members were interviewed to capture deeper social and economic knowledge. Findings reveal pronounced social impacts, with 97.4% of respondents identifying adverse health outcomes and 91.4% reporting greater vulnerability among children and youth. Cultural changes were evident through declining traditional food habits (87.9%), disruption of family routines (81%), and reduced cooking skills (75%). Regression analysis demonstrated a statistically significant positive association between fast-food frequency and BMI ($R = 0.30$ at $p < 0.05$), though the relationship remained modest due to external lifestyle and sampling factors. Economically, fast food contributed to industrial growth (89.7%) and tax revenue (81.9%) but simultaneously imposed substantial financial burdens, including rising healthcare costs (94.8%), pressure on low-income families (94%), and household budget inflation (89.7%). Overall, the study highlights how urban food culture, behavioural patterns, and biological responses interact within a broader socio-ecological system, emphasizing the need for targeted public health interventions and policies to mitigate the long-term social and economic risks associated with fast-food dependency.

Keywords: Fast-food consumption; socio-economic impacts; sustainable development; urban health; Wattala–Mabola; Human Disease Ecology Model

1. Introduction and Background

Urban food consumption patterns have transformed significantly across rapidly developing Asian contexts due to urbanization, rising incomes, changing lifestyles, and the expansion of both local and global food chains. Among these changes, fast-food consumption has become a prominent feature of urban living because of its convenience, affordability, and association with modern lifestyles. Fast foods are typically energy-dense, high in saturated fats, sugar, and sodium, providing immediate accessibility while offering limited nutritional value (World Health Organization, 2016). The growth of fast-food systems extends beyond dietary trends, representing a socio-economic phenomenon that reshapes household consumption behaviour, local labour markets, and traditional food cultures (Kendall, 2023).

Across Asia, the socio-economic consequences of fast-food consumption are increasingly evident. In India, rapid economic growth and urbanization have fuelled a surge in fast-food culture, particularly among younger populations, as outlets leverage globalization and marketing to shape dietary behaviours (Swaminathan & Viswanathan, 2016; Keshari & Mishra, 2016). In Pakistan, studies of college students show that fast-food consumption is strongly influenced by peer behaviour, time constraints, and marketing, with Westernized dietary norms reinforcing its appeal among youth (BMC Public Health, 2023). This trend contributes to unhealthy weight gain, insulin resistance, and other diet-related health concerns. In Malaysia, youngster's consumption is associated with sociodemographic traits such as ethnicity, school locality, and frequency of eating out, highlighting how accessibility and urban lifestyles shape fast-food intake (Man et al., 2021). Collectively, these patterns suggest that in many Asian contexts, fast food has evolved from a dietary choice to a socio-economic symbol of modern urban living, closely tied to income, cultural attitudes, and food environments. Sri Lanka appears to be following a similar trajectory under its own urban transformation.

The Wattala–Mabola Urban Council area in Sri Lanka provides a suitable context to examine the socio-economic implications of fast-food consumption. This area is characterized by a dense concentration of middle and high-income households, numerous educational institutions, busy commercial zones, and well-connected transport corridors facilitating access to fast-food outlets. Many restaurants are located within residential neighbourhoods and near schools, increasing exposure among children, youth, and working adults. Data from this study indicate that fast-food consumption is highest among children and youth aged 0–29 years (80.1%), middle and high-income earners (71.5%), and undergraduates and students below 18 years (67.2%), with 72.4% of respondents living within 1–3 km of a fast-food outlet (Mubashshira, 2026). Factors such as taste preferences, convenience, peer influence, workload, time constraints, and promotional discounts further reinforce these consumption patterns. The combination of accessibility, economic capacity, and socio-cultural influences has created a distinctive urban food environment in which fast foods are embedded in daily routines.

The socio-economic impacts of fast-food consumption are multifaceted. Studies indicate that reliance on fast food among urban populations, particularly youth and college students, has significant implications for both health and lifestyle. Those findings suggest that fast-food consumption in urban Asian settings represents a broader socio-economic phenomenon, linked to lifestyle, social interactions, and health outcomes. The expansion of fast-food systems also intersects with local economies, influencing employment in the food service sector while affecting small-scale traditional food vendors and local agricultural producers (Kendall, 2023).

Despite its relevance, research specifically examining the socio-economic impacts of fast-food consumption within the Wattala–Mabola Urban Council area remains limited. No previous study has comprehensively addressed these dimensions in the local context. Given the high concentration of fast-food outlets, significant consumption among youth, and a diverse mix of middle and high-income households, the area provides a timely and relevant context for investigation. This study aims to fill this research gap and generate valuable insights into the socio-economic dimensions of fast-food consumption in an urban Sri Lankan setting, contributing to the development of sustainable, culturally appropriate, and health-conscious food practices.

2. Literature Review

2.1 Social Impacts

▪ Health Impacts

Global Overview:

Previous studies indicate that the poor nutritional quality of fast food, combined with high levels of salt, saturated fats, and trans fatty acids, may contribute to the prevalence of hypercholesterolemia, hypertension, type 2 diabetes mellitus, obesity, and cardiovascular diseases, particularly in Western societies (Jahan et al., 2020). Reviews of the short and long-term health consequences of fast-food consumption demonstrate that obesity is widespread and predisposes individuals to chronic conditions such as heart disease and diabetes. Fast foods contain refined sugars that can cause rapid spikes in blood sugar levels, leading to fatigue, decreased energy, frequent hunger, and impairments in brain function and memory. Excessive consumption of fast food over weeks, months, or years can result in long-term health problems. High intake of saturated fats can elevate cholesterol levels, which increases the risk of heart disease, hypertension, and stroke (Jia et al., 2022).

A study of 33,594 children aged 3–14 in the United Kingdom found that fast-food consumption was particularly associated with negative health outcomes, 27.1 percent were overweight or obese, and 12.6 percent were classified as obese (Fraser & Edwards, 2010). Another study of boys aged 13–15 revealed that fast-food consumption had significant negative effects, including increased BMI SD scores ($b = 0.08$, 95% CI = 0.03–0.14), increased body fat percentage ($b = 2.06$, 95% CI = 1.33–2.79), and increased body fatness (OR = 1.23, 95% CI = 1.02–1.49) (Fraser et al., 2012).

In Saudi Arabia, a study found that 25 percent of female students were overweight or obese, with 74.5 percent of these students consuming fast food 1–2 times per week. A significant positive association was observed between increased consumption of fish sandwiches and higher BMI (Alfawaz, 2012). In Iraq, fast food consumption was strongly linked to obesity, elevated blood pressure, and cardiovascular disease due to its high fat and carbohydrate content, although its association with diabetes was comparatively low (Mahmood & AbdulWahab, 2020).

A study in India reported that 74.4 percent of consumers were aware of the negative health effects of fast-food consumption, which included increased risks of mental health disorders (30.8%), weight gain (6.4%), cancer (30.8%), diabetes (21.8%), obesity (16.7%), high stress (33.3%), memory loss (9%), and cardiovascular disease (25.6%) (Hajare Wani & Sarode, 2018). Another study conducted in the Lucknow district found alarming obesity prevalence among school children aged 9–13: 100% of 9-year-olds were obese at stage 1, 42.8% of 10-year-olds at stage 3, 8.6% of 11-year-olds at stage 3, 36.3% of 12-year-olds at stage 2, and 8.3% of 13-year-olds at stage 3 (Singh & Mishra, 2014).

These findings underscore that the health impacts of fast-food consumption are global. Particularly in developing countries, an increasing number of children and young people are experiencing health problems associated with elevated fast-food consumption.

Sri Lanka Overview:

A study on fast-food consumption among students of Sri Lankan government universities indicated that fast-food intake is increasing among children and youth, with unhealthy eating habits particularly prevalent among university students. These habits have been shown to adversely affect nutrition and health. The study found that 32.3 percent of students were overweight according to BMI, and a positive relationship was observed between fast-food consumption and BMI, with 30.3 percent of students consuming fast food 2–3 times per week (Saujan et al., 2024). A study conducted in the Kiriella area of Ratnapura revealed that fast-food consumption is associated with overweight among youth; 19 percent of high school students, 28 percent of university students, and 3 percent of working adults were overweight. Furthermore, 50 percent of overweight cases were specifically related to occupational status, highlighting a close link between fast-food consumption and excess weight (Priyanth & Dassanayaka, 2022). Another study found that approximately 54 percent of students consumed fast food more than once a day, with about 7 percent of women overweight and 2 percent obese. Among men,

around 12 percent were overweight, placing them at a higher risk of developing diet-related non-communicable diseases (Jayasinghe & De Silva, 2014).

▪ **Other Social Impacts**

Fast-food consumption in South Africa has had a significant impact, particularly among youth and students. It is often seen as a symbol of modernity and progress, providing convenience and opportunities for social interaction within an urban lifestyle. Students are encouraged to rely on fast food due to shifts toward a more independent lifestyle, the availability of diverse food choices, limited cooking skills, and constraints on time and resources. Fast-food restaurants also function as social hubs where individuals gather for entertainment and leisure (Rabotata & Malatji, 2021). A study on the effects of fast-food consumption on family life in Nigeria found that people do not consume fast food because of a lack of kitchen utensils or because it is more economical than home-cooked meals. Rather, consumption is driven by taste, leisure, entertainment, and work demands. However, frequent fast-food consumption has been reported to contribute to children becoming less active, a decline in cooking skills, a preference for fast food over home-cooked meals, and a dislike of traditional foods among some family members. Additionally, mothers have less time to teach children about healthy eating habits and table manners, awareness of proper nutrition is low, and family time is reduced (Ejike & Obeagu, 2018). In Bangladesh, fast-food outlets often target schools and workplaces. Economic inequalities have made minority communities more dependent on fast food. As traditional family meals are increasingly replaced by fast-food options, cultural and familial bonds are affected. Furthermore, peer influence and advertising play a major role in shaping the consumption patterns of young people (Nusrat, 2022).

2.2 Economic Impacts

The article *Burgernomics: The Impact of Fast Food on the Economy* highlights several economic impacts of fast-food consumption:

Employment: The restaurant industry alone employs over 15 million people in the United States; however, significant gaps exist in minimum wage levels and workers' rights.

Income inequality: Fast-food executives earn hundreds of times more than their workers. Employees have been advocating for a minimum wage of \$15, which has led to government subsidies to support low-income workers.

Health costs: The ingredients commonly found in fast food contribute to various health problems, resulting in high medical expenses and reduced employee productivity (Faster Capital, n.d.).

The convenience, affordability, and taste of fast food make it a popular choice in Portugal, particularly among higher education students. Most students consume fast food several times a month, spending approximately eight euros per meal. This reflects a shift in spending patterns toward quicker and cheaper food options. Additionally, limited student budgets and the increased healthcare costs associated with frequent fast-food consumption contribute to economic strain (Oliveira & Raposo, 2024). In China, fast-food consumption has several economic impacts. It helps reduce income gaps by providing employment opportunities through food distribution and packaging processes. The fast-food industry also stimulates the growth of related sectors, including food packaging, delivery services, and traditional catering. Moreover, it promotes economic efficiency by allowing individuals to save time on meal preparation (Song, 2023).

Although few studies in Sri Lanka have examined fast food consumption, mostly focusing on university students and related health concerns, showing high intake among youth and associated health risks. However, there is limited research on urban dwellers, particularly regarding both health and economic impacts. This study addresses this gap by exploring fast food consumption patterns, socio-cultural influences, and potential consequences among residents of the Wattala–Mabola urban area.

3. Theoretical Background: Human Disease Ecology

The human disease ecology model provides a framework to understand how health outcomes are shaped by the interaction of social, economic, behavioral, and environmental factors. In the context of urban dietary patterns, such as fast-food consumption, this model highlights that increased exposure to calorie-dense foods, combined with socio-economic and lifestyle factors, can influence the prevalence of non-communicable diseases, including obesity. In the Wattala–Mabola Urban Council area, empirical evidence from this study shows a positive relationship between monthly fast-food consumption and BMI, indicating that higher consumption is associated with increased body weight. The human disease ecology perspective offers a theoretical lens to interpret these socio-economic and health-related patterns, emphasizing the interconnectedness of environment, behavior, and health. A more detailed application of this model to the study results is discussed in the Results and Discussion section.

4. Methodology

4.1 Study Area

The study was conducted in the Wattala–Mabola Urban Council area, which falls under the Wattala Divisional Secretariat Division in the Gampaha District of Sri Lanka’s Western Province. The division comprises 46 Grama Niladhari Divisions, of which six form the fully urbanized administrative units governed by the Wattala–Mabola Urban Council. Geographically, the area lies near 7.0021° N latitude and 79.9025° E longitude and is bordered by Negombo Lagoon to the north, the Kelani River to the south, the Ja-Ela–Mahara Division to the east, and the Indian Ocean to the west. With a population of about 31,471, the locality is characterized by a culturally diverse and predominantly urban community experiencing rapid spatial and socio-economic transformation. This area was selected for the study as no prior research has specifically examined the socio-economic implications of fast-food consumption within this urban context. Its high level of development, accessibility, and relevance to the study objectives also make it an appropriate setting for investigating emerging urban dietary behaviors.

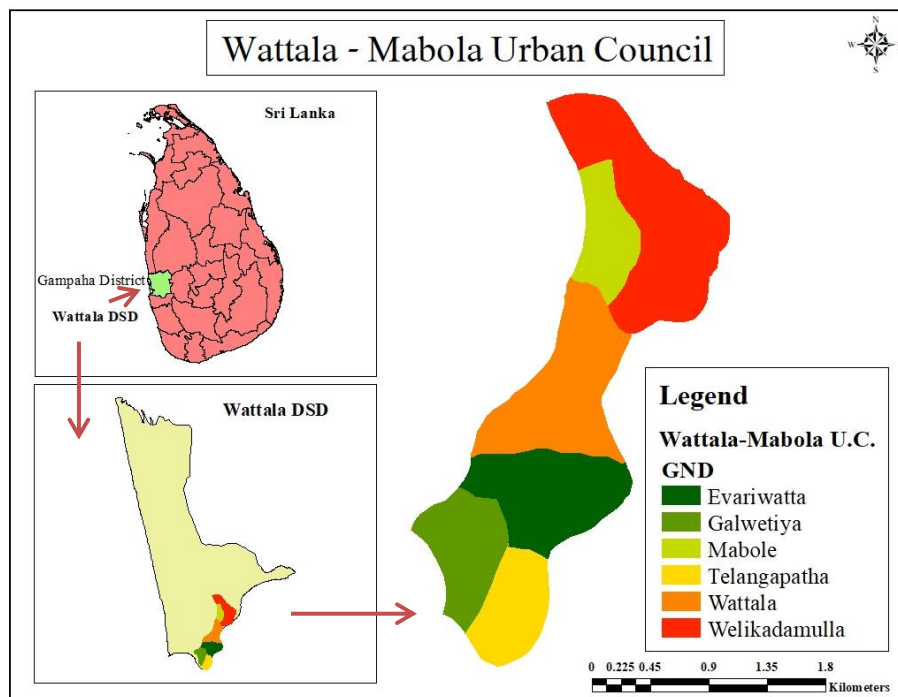


Figure 1: Wattala-Mabola Urban Council Study Area Map

4.2 Data and Data Collection Methods

This study used both primary and secondary data, with primary data serving as the core source of evidence. A structured, mixed-method questionnaire was administered to selected urban residents to capture their fast-food consumption patterns and associated socio-economic characteristics. To complement the survey findings, semi-structured interviews were conducted with three key stakeholder groups: five health officers attached to the Wattala Medical Officer of Health Office and the Wattala–Mabola Urban Council, seven government officials from the Urban Council and the Divisional Secretariat, and eight community members. In total, 20 interviewees contributed detailed insights into the health and socio-economic implications of fast-food consumption in the area.

Secondary information was obtained from research publications, official documents, books, digital sources, and the 2024 administrative report of the Wattala Divisional Secretariat Division. These sources supported the triangulation of primary data and provided a broader contextual understanding for the study.

4.3 Sampling Methods

Both probability and non-probability sampling techniques were applied in this study. A stratified sampling approach was used to select survey participants from the six Grama Niladhari Divisions within the Wattala–Mabola Urban Council area. These divisions are Telangapatha, Evariwatta, Wattala, Mabola, Galwetiya, and Welikadamulla, together represent a population of 31,471 and include a diverse mix of ethnic groups. To ensure adequate representation, each ethnic group was treated as a separate stratum, and samples were distributed proportionately across the major ethnic categories.

Given practical constraints such as time limitations and accessibility challenges, 116 respondents were randomly selected from the six divisions. Questionnaires were therefore distributed following a ratio of 300:1, ensuring broad coverage of urban households while maintaining feasibility for the researcher.

In addition to the survey, qualitative data were collected through interviews using a purposive non-probability sampling method. A total of 20 individuals were selected based on their relevance to the study context, allowing for richer insights into the social and economic dimensions of fast-food consumption.

The number of samples drawn from each Grama Niladhari Division is summarized in the following table.

Table 1: Questionnaire Sampling Table

Grama Niladhari Divisions	Ethnic Groups					Total Samples
	<i>Sinhala</i>	<i>Tamil</i>	<i>Muslim</i>	<i>Burgar</i>	<i>Other</i>	
Telangapatha	9	3	2	1	1	16
Evariwatta	12	4	1	1	1	19
Wattala	7	4	1	1	-	13
Mabola	6	2	10	1	-	19
Galwetiya	5	5	1	-	-	11
Welikadamulla	12	6	18	2	-	38
Total Samples						116

Source: (The Annual Report of the Wattala Divisional Secretariat Division, 2024)

Note: The important of stratified sampling method

It was done based on ethnicity across the 6 GN divisions where more migrant population can be encountered, to ensure proportional representation. Within each ethnic group, participants were randomly selected, which naturally included people of different ages, income levels, and education backgrounds. This allowed the study to cover all key socio-demographic categories while analysing patterns among fast food consumers.

4.4 Data Analysis

Data analysis was conducted using both quantitative and qualitative techniques in line with the study objective. Quantitative data obtained through the questionnaire were analyzed using descriptive and inferential statistical methods, while qualitative information from interviews and open-ended responses was examined through thematic analysis.

Descriptive statistics were used first to summarize the socio-economic impacts reported by respondents. Inferential analysis was then performed using simple linear regression at the 0.05 significance level, with Body Mass Index (BMI) as the dependent variable and the monthly frequency of fast-food consumption as the independent variable. This analysis helped determine whether an increase in fast-food consumption was associated with changes in BMI. External factors influencing BMI were excluded to isolate the direct relationship. The interpretation of the regression results also drew on the Human Disease Ecology Model, which provides a conceptual basis for understanding how behavioural factors such as dietary practices interact with socio-economic and environmental conditions to influence health outcomes. This theoretical perspective guided the interpretation of how increased fast-food consumption may contribute to elevated BMI within the study population.

Qualitative data related to social and economic impacts were analysed using a thematic approach. Key themes were developed around physical and mental health, household economic pressures, and broader socio-economic consequences identified through interviews, questionnaire narratives, and secondary literature.

The results are presented using pie charts, bar graphs, and descriptive summaries for clarity. Microsoft Excel was used to manage the dataset, perform statistical calculations, and create visualizations, while ArcGIS 10.8 was used to prepare the map of the study area.

The simple regression analysis was based on the following equation:

$$y = a + bx$$

5. Results and Discussion

5.1 Social Impacts of Fast-Food Consumption

The social implications of rising fast-food consumption in the study area reveal a complex interplay between changing lifestyles, family routines, and community interactions. The responses gathered illustrate that fast food is now embedded in everyday social behaviour, shaping how people eat, interact, and negotiate their cultural food identity. As illustrated in **Figure 2**, a substantial proportion of participants (89.7%) noted that the expansion of fast-food outlets has increased the availability and accessibility of food choices. While this wider choice encourages convenience, respondents also emphasized several negative social outcomes. For instance, 77.6% reported that fast-food consumption has become a common facilitator of social gatherings, especially among youth, subtly shifting social norms around eating practices.

A strong concern highlighted by 87.9% of respondents was the gradual decline of traditional dietary habits, indicating a cultural shift that may have long-term implications for food heritage. Changes within the household were also evident 81% believed that frequent fast-food use disrupts family dynamics, contributing to reduced home-cooked meals and shared mealtime routines. This is complemented by the view of 81% who felt that family time is diminishing as individuals increasingly opt for quick meals rather than collective dining experiences.

Health-related stigma and concerns emerged as the most dominant theme, with 97.4% identifying adverse health impacts as a major social consequence. This aligns with public health discussions on how lifestyle-driven food choices can influence community wellbeing. Moreover, 91.4% stressed that children and adolescents are particularly vulnerable to fast-food habits, which may shape long-term behavioural patterns and health outcomes. Additional concerns included a reduction in cooking skills (75%) and, among a small proportion (0.9%), the emergence of an excessive or “greedy” desire for fast food.

Overall, the results illustrate that while fast-food consumption contributes to convenience and social bonding, it simultaneously affects cultural practices, family cohesion, and community health perceptions. These findings underscore the broader social dimensions of dietary transitions occurring within urban Sri Lankan settings.

The assessment of self-reported changes in Body Mass Index (BMI) provides important insight into how dietary behaviours, particularly fast-food consumptions are influencing physical health within the study area. The responses show a clear pattern that aligns with broader nutritional and epidemiological concerns. As shown in **Figure 3**, more than half of the participants (57.8%) reported an increase in their BMI over time. This tendency suggests that regular reliance on calorie-dense, commercially prepared meals may be contributing to gradual weight gain among urban residents. In contrast, only a very small proportion (2.6%) indicated a decrease in BMI, while 39.7% stated that their BMI had remained unchanged.

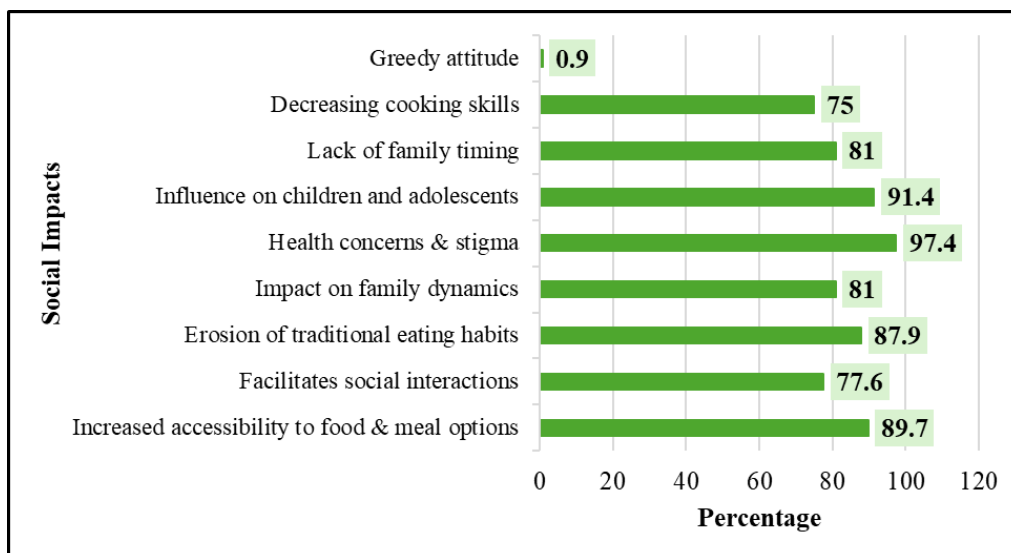


Figure 2: Social Impacts of Fast-Food Consumption in Wattala-Mabola Urban Council Area

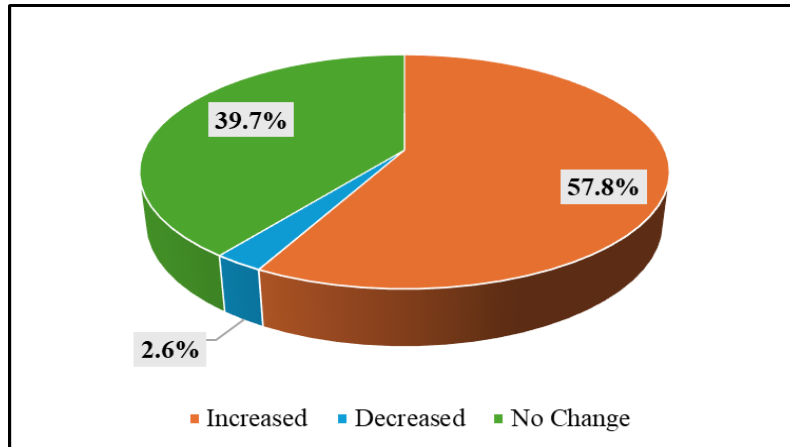


Figure 3: Self-Reported Changes in BMI Among Respondents in the Wattala–Mabola Urban Council Area

Taken together, these findings demonstrate a clear association between frequent fast-food consumption and rising BMI levels among a considerable portion of the respondents. The predominance of individuals reporting weight gain reflects a broader dietary shift toward convenience-oriented food choices and underscores the emerging health risks linked to such patterns. In order to substantiate this observed relationship, a simple regression analysis was carried out, and the corresponding results are presented below.

To examine the association between fast-food consumption and body mass index (BMI) among urban dwellers, a simple regression analysis was conducted. In this analysis, the monthly frequency of fast-food consumption was treated as the independent variable, while the BMI of respondents was the dependent variable. External influencing factors were deliberately excluded to isolate the direct relationship between consumption patterns and BMI. The results of this regression provide insight into how increased fast-food intake corresponds with changes in BMI among the population.

Based on that, the regression equation is as follows.

$$Y = 25.0272 + 0.1756 X$$

Y = BMI

X = the monthly frequency of fast-food consumption

Table 2: Regression Statistics

<i>Regression Statistics</i>	
Multiple R	0.302001748
R Square	0.091205056
Adjusted R Square	0.08323317
Standard Error	3.919193817
Observations	116

The correlation between monthly fast-food consumption and body mass index (BMI) is reflected by a correlation coefficient of 0.30, indicating a positive association between the two variables. This suggests that higher frequency of fast-food consumption is associated with increased BMI among respondents. The R-squared value of the regression model is 0.0912, implying that while monthly consumption contributes to variations in BMI, it explains only a small proportion of the total variability. The relatively low R-squared is understandable given that external factors influencing BMI were excluded from the model.

The standard error of the regression equation is 3.92, which is below the threshold of 5, suggesting that the regression line adequately represents the distribution of the observed data. This analysis was conducted using a sample of 116 respondents, providing a focused estimate of the relationship between fast-food consumption frequency and BMI in the study area. Overall, the results demonstrate a moderate but meaningful positive correlation, supporting the notion that frequent fast-food intake can contribute to higher BMI levels among urban dwellers.

Table 3: ANOVA Table

ANOVA					
	<i>df</i>	<i>SS</i>	<i>MS</i>	<i>F</i>	<i>Significance F</i>
Regression	1	175.732199	175.7322	11.44084	0.000985214
Residual	114	1751.04914	15.36008		
Total	115	1926.781339			

The F-test for the regression model yielded a significance value of 0.0009. Given that this value is below the 0.05 alpha threshold, the results indicate that the regression equation is statistically significant and can be considered a reliable representation of the relationship between monthly fast-food consumption and BMI.

Table 4: Output

	<i>Coefficients</i>	<i>Standard Error</i>	<i>t Stat</i>	<i>P-value</i>
Intercept	25.02718923	0.455419255	54.95417	7.03E-84
Consuming Times -per month (x)	0.175567281	0.051905652	3.382431	0.000985

The results presented in Table 4, indicate that the p-value for the monthly frequency of fast-food consumption is 0.0009, which is below the significance level of $\alpha = 0.05$. This demonstrates that changes in Body Mass Index (BMI) are significantly associated with an increase in the frequency of fast-food consumption. Furthermore, the positive correlation coefficient of 0.1756 suggests a direct relationship between the variables, indicating that higher monthly consumption of fast food among urban residents is associated with an increase in BMI. The relationship between monthly fast-food consumption and Body Mass Index (BMI) among urban residents underscores significant health implications. The scatter plot with the regression line (Figure 4) reveals a positive association between BMI and the monthly frequency of fast-food consumption, indicating that higher consumption is linked to increased BMI. The regression line confirms this trend, suggesting a measurable connection between dietary habits and weight outcomes. These findings imply that frequent fast-food consumption contributes to negative health outcomes, including overweight, obesity, diabetes, and cardiovascular conditions. While external factors such as genetics, physical activity, and other lifestyle choices also influence health, the statistical analysis highlights the significant impact of fast-food consumption on BMI.

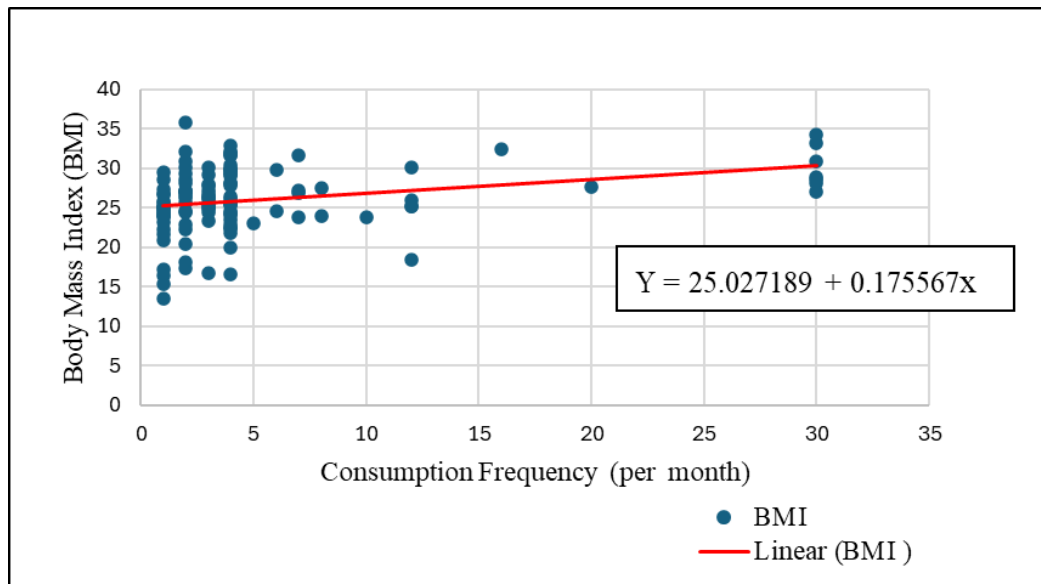


Figure 4: Scatter Plot with Regression Line: Monthly Fast -Food Consumption Frequency and Body Mass Index (BMI)

From the perspective of the Human Disease Ecology (HDE) model, these results reflect the interaction of environmental, behavioural, and biological factors. Environmentally, the Wattala–Mabola urban area represents a highly accessible fast-food environment, with numerous outlets located near residential settlements, schools, and commercial zones. This urban food landscape functions as an ecological driver that encourages frequent consumption of energy-dense, nutrient-poor foods, thereby shaping dietary behaviours in ways that contribute to weight gain.

The findings of this study can be interpreted through the lens of the Human Disease Ecology (HDE) model, which situates health outcomes within a broader ecological context. The urban food environment in Wattala–Mabola, characterized by a dense concentration of fast-food outlets, functions as an environmental factor that facilitates frequent consumption. Lifestyle practices, including convenience-driven eating, taste preferences, peer influence, and time constraints, represent behavioural factors that interact with individual biological processes, such as metabolism and susceptibility to obesity-related conditions, to influence disease risk. The positive relationship identified through regression analysis between monthly fast-food consumption and Body Mass Index quantitatively reflects this ecological interaction, emphasizing that the health impacts of fast-food consumption are shaped by the interplay of environmental, human activities, and biological determinants.

Supporting this, interviews with health officials, government officers, and members of the public revealed multiple social impacts of increased fast-food consumption in the Wattala–Mabola Urban Council area. These impacts were broadly categorized into physiological health disorders, psychological health effects, addiction and youth behaviour, effects on family and cultural practices, peer group preferences, and lifestyle changes. Together, the quantitative and qualitative findings illustrate that fast-food consumption is not merely a dietary habit but a socio-ecological phenomenon, where the urban environment, social behaviours, and individual biology collectively shape health outcomes. This integrated perspective underscores the need for interventions that address both personal choices and the broader social and environmental contexts influencing dietary behaviour.

- **Physiological Health Disorders**

Health officials consistently highlighted that frequent fast-food consumption contributes to a range of non-communicable diseases. These include overweight, obesity, diabetes, digestive disorders, high cholesterol, and nutrition-related diseases (*Respondent 1*). In particular, school students were noted to be increasingly affected by overnutrition and malnutrition, with a notable proportion exhibiting

overweight or obesity (*Respondent 2*). Respondents also emphasized that unhealthy ingredients in fast foods, such as high levels of sugars, refined carbohydrates, preservatives, colorants, and monosodium glutamate, are linked to chronic health conditions, including diabetes, cancer, and bone-related disorders (*Respondents 1 and 2*).

- **Psychological Health Disorders**

Interviewees reported that excessive fast-food consumption also has psychological implications, particularly among children and youth. These include increased fatigue, reduced engagement in learning, decreased physical activity, and poor eating habits, including avoidance of nutritious home-cooked meals (*Respondents 1 and 9*). In some cases, high body weight resulting from frequent fast-food consumption was associated with negative self-perception, stress, and mental health issues such as depression (*Respondents 2 and 8*).

- **Addiction and Youth Behaviour**

The interviews highlighted that fast food has become addictive among children and youth due to its taste, convenience, affordability, and visual appeal. Many parents also encourage fast-food consumption for convenience and as a symbol of modernity (*Respondents 1 and 2*). Additionally, fast-food vendors strategically target the preferences of young consumers, offering foods with attractive colors, shapes, and flavors, reinforced through advertisements and media exposure, further fostering consumption habits (*Respondent 3*).

- **Impact on Family and Cultural Practices**

Frequent fast-food consumption has disrupted traditional family practices. Respondents noted that family mealtimes, which once encouraged interaction and bonding, are now replaced by individual consumption of fast foods (*Respondent 6*). Additionally, peer influence and economic pressures sometimes lead children to engage in dishonest behaviours to obtain fast food, contributing to cultural degradation and a decline in traditional food consumption (*Respondents 13 and 19*).

- **Peer Group Preferences**

Fast food has emerged as a social activity among youth, particularly within peer groups. Respondents emphasized that consumption is often associated with entertainment and socializing, reinforcing the trend as a marker of modern youth culture (*Respondents 13 and 20*).

- **Impact on Lifestyle**

Finally, interviewees indicated that urban lifestyles, characterized by busy schedules and limited time for home cooking, contribute to higher fast-food consumption. Compared to rural residents, urban dwellers are more likely to rely on fast food for convenience, reflecting lifestyle-driven dietary patterns (*Respondents 6 and 17*).

Fast-food consumption in the Wattala–Mabola Urban Council area has far-reaching social implications, influencing health, behaviour, and cultural practices in urban communities. It is associated with both physiological and psychological health risks, including overweight and obesity, as well as addictive eating habits, particularly among youth. At the same time, it affects family dynamics and peer interactions, contributing to shifts in meal routines, reduced home-cooked meals, and broader lifestyle adaptations. These changes reflect not only local patterns but also global trends, highlighting how modern urban diets can shape social norms, cultural continuity, and public health landscapes in ways that extend beyond individual choice.

From a sustainable urban development perspective, the findings indicate that the rapid expansion of fast-food outlets in the Wattala–Mabola Urban Council area reflects an urban food environment driven primarily by convenience and commercial efficiency rather than long-term social sustainability. While increased accessibility supports fast-paced urban lifestyles, frequent fast-food consumption contributes to unhealthy dietary patterns, rising BMI levels, and increasing public health risks, raising concerns aligned with **SDG 3 (Good Health and Well-being)** and **SDG 12 (Responsible Consumption and**

Production). The observed decline in traditional food practices and family-based meals further highlights challenges related to cultural continuity and social cohesion, which are central to **SDG 11 (Sustainable Cities and Communities)**. These findings suggest that sustainable urban development in Sri Lanka must prioritize socially supportive food environments that promote healthy eating behaviors, preserve cultural food traditions, and strengthen community well-being alongside urban growth.

5.2 Economic Impacts of Fast-Food Consumption

The economic impacts of fast-food consumption in the Wattala–Mabola Urban Council area are multifaceted, reflecting both positive contributions to the urban economy and negative pressures on households. As shown in Figure 5, 79.3 percent of respondents indicated that fast-food businesses contributed to job creation, 66.4 percent noted their role in supporting the urban economy, 89.7 percent associated them with industrial growth, and 81.9 percent recognized the generation of tax revenue, particularly through restaurants and government collections.

At the same time, respondents highlighted several adverse economic consequences. These include financial pressures on low-income families (94 percent), rising health care costs (94.8 percent), inflation in household budgets (89.7 percent), negative impacts on local businesses (87.9 percent), economic inequality (89.7 percent), reduced productivity (77.6 percent), and environmental costs (86.2 percent). Notably, the increase in health care costs emerged as a particularly significant concern among urban dwellers, reflecting the broader socio-economic burden associated with fast-food consumption.

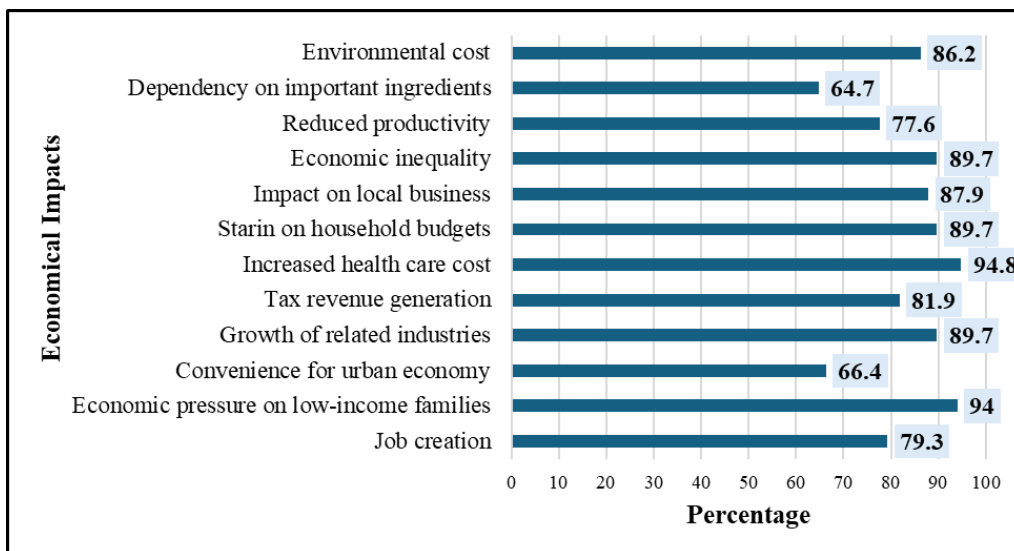


Figure 5: Economic Impacts of Fast-Food Consumption in Wattala-Mabola Urban Council Area

The influence of fast-food consumption on the monthly expenditure of urban residents reflects its broader economic burden at the household level. **Figure 6** shows that 69% of respondents reported a slight increase in their monthly spending due to fast-food purchases, 13.8% reported a significant increase, and 17.2% indicated no noticeable impact. Only a small proportion stated that fast food consumption did not affect their monthly expenditure

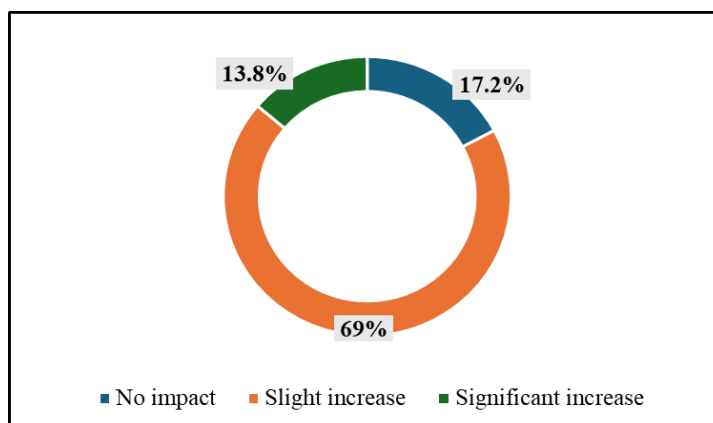


Figure 6: Impact of Fast-Food Consumption on Monthly Household Expenditure in the Wattala–Mabola Urban Council Area

Overall, the majority of urban dwellers experience at least a slight financial impact, highlighting the role of fast-food consumption in shaping household economic behaviour.

Interviews with respondents further elaborated on these economic impacts, which can be thematically categorized into health costs, family income, and food accessibility.

- **Health Costs**

Respondents noted that frequent consumption of fast food, which is relatively expensive, not only increases household spending but may also contribute to future health-related expenses due to diet-related diseases (*Respondent 5*).

- **Family Income**

Financial pressures were particularly pronounced among low-income households. While urban residents with higher incomes can afford fast food, those with limited earnings often experience economic strain when attempting to maintain such dietary habits. For example, some government officials with modest salaries tend to avoid fast food due to cost, whereas others face financial difficulties from regular consumption despite limited income (*Respondent 8*). Preparing meals at home was highlighted as a cost-effective alternative that ensures adequate nutrition, while reliance on fast food increases expenditure and associated health costs (*Respondent 13*).

- **Food Accessibility**

The proximity of fast-food outlets also influences consumption patterns and household spending. Respondents explained that easy access to restaurants encourages more frequent purchases, which can unintentionally raise monthly expenses (*Respondent 10*).

Fast-food consumption in the Wattala–Mabola Urban Council area presents a complex economic landscape, with both benefits and costs shaping household and urban-level outcomes. While the industry contributes to employment, industrial growth, and public revenue, it also generates financial pressures for urban residents, particularly among low-income households. Increased spending on fast food, rising healthcare costs associated with diet-related illnesses, and inflation in household budgets highlight the broader economic trade-offs of convenience-oriented urban diets. These patterns align with global observations that, although fast-food industries can stimulate economic activity, the associated household-level financial burdens and health expenditures represent significant long-term challenges to inclusive and equitable urban development.

From a sustainable resource management and urban development perspective, the economic impacts of fast-food expansion in the Wattala–Mabola Urban Council area extend beyond employment creation

and revenue generation to include significant environmental costs that place additional pressure on urban resources. While the fast-food sector contributes to industrial growth, jobs, and tax income, these benefits are offset by rising household expenditure, increasing healthcare costs, and financial strain on low-income families, raising concerns related to **SDG 8 (Decent Work and Economic Growth)** and **SDG 3 (Good Health and Well-being)**. Importantly, fast-food consumption is closely associated with the extensive use of single-use plastics, shopping bags, and packaging materials, along with unstructured waste disposal practices, which increase urban council waste management costs and reduce resource efficiency. These environmental externalities represent hidden economic burdens for urban authorities and households, aligning with **SDG 12 (Responsible Consumption and Production)** and **SDG 11 (Sustainable Cities and Communities)**. Overall, the findings suggest that sustainable urban development in Sri Lanka requires economic planning that accounts not only for market growth but also for environmental management costs, equitable resource use, and long-term urban resilience.

6. Conclusion

This study demonstrates that fast-food consumption in the Wattala–Mabola Urban Council area represents a significant socio-economic challenge embedded within the dynamics of urbanization in Sri Lanka. Rather than being a simple matter of individual dietary choice, fast-food consumption reflects broader transformations in urban lifestyles, food accessibility, cultural practices, and economic conditions. These interconnected factors collectively shape health outcomes, household well-being, and the sustainability of urban communities.

The findings indicate that frequent fast-food consumption is strongly associated with adverse health outcomes, particularly among children and youth, and contributes to the gradual erosion of traditional dietary practices and family-based food routines. Although convenience and diversity of food choices are recognized benefits, they are increasingly outweighed by rising physical and psychological health risks. The statistically significant relationship observed between fast-food consumption and Body Mass Index further underscores its relevance as a public health concern within urban settings, even when accounting for external lifestyle and socio-economic factors.

From an economic perspective, fast food plays a dual role in urban development. While it contributes to employment, industrial growth, and public revenue, it simultaneously imposes financial pressures on households through increased food expenditure and healthcare costs. These burdens are felt most acutely by low-income families, highlighting issues of equity and inclusiveness in urban economic systems. Additionally, the expansion of fast-food outlets poses challenges to local food economies, raising concerns about the long-term resilience of traditional and small-scale food sectors.

Interpreted through a sustainable urban development framework, the results emphasize the need to align urban food environments with public health, cultural sustainability, and social equity objectives. The Human Disease Ecology perspective illustrates how environmental exposure, behavioral patterns, and biological responses interact within urban contexts to influence disease risk and socio-economic outcomes. Addressing the impacts of fast-food consumption therefore requires integrated and multi-sectoral interventions, including nutrition education, urban planning regulations, promotion of healthier food environments, and support for culturally rooted and locally sourced food systems.

In conclusion, this research provides evidence that sustainable urban development in Sri Lanka must extend beyond infrastructure and economic growth to include food systems and lifestyle-related health considerations. By integrating public health, social well-being, and economic sustainability into urban planning and policy frameworks, Sri Lankan cities can move toward more resilient, equitable, and health-supportive urban futures.

References

- Abbas, S., Naz, M., Gillani, S.M.A., Afzal, S., Jabeen, N. and Manzoor, A. (2022) 'Analyze the effects of fast food on the health of college going students', *PJMHS*, 16(2), p. 1053. <https://doi.org/10.53350/pjmhs221621053>
- Alfawaz, H.A. (2012) 'The relationship between fast food consumption and BMI among university female students', *Pakistan Journal of Nutrition*, 11(5), pp. 406–410. <https://doi.org/10.3923/pjn.2012.406.410>
- BMC Public Health (2023) 'Using the theory of planned behavior to predict factors influencing fast-food consumption among college students', *BMC Public Health*, 23, Article 987. <https://doi.org/10.1186/s12889-023-15923-1>
- Divisional Secretariat – Wattala (2023) Sampath Pathikada: Divisional Secretariat Division – Wattala. Unpublished internal document.
- Ejike, B.N. and Obeagu, E.I. (2018) 'Consumption of fast foods and their effects on family lifestyle in Aba North L.G.A of Abia State', *International Journal of Current Research in Medical Sciences*, 4(4), pp. 34–42.
- Faster Capital (n.d.) *Burgernomics: The impact of fast food on the economy*. Available at: https://www.fastercapital.com/Burgernomics_The_Impact_of_Fast_Food_on_the_Economy.html (Accessed: 3 November 2024).
- Fraser, L.K. and Edwards, K.L. (2010) 'The association between the geography of fast food outlets and childhood obesity rates in Leeds, UK', *Health & Place*, 16(6), pp. 1124–1128. <https://doi.org/10.1016/j.healthplace.2010.07.003>
- Fraser, L.K., Clarke, G.P., Cade, J.E. and Edwards, K.L. (2012) 'Fast food and obesity', *American Journal of Preventive Medicine*, 42(5), pp. e77–e85. <https://doi.org/10.1016/j.amepre.2012.02.007>
- Hajare Wani, P. and Sarode, N. (2018) 'Impact of fast food consumption on health', *International Journal on Recent Trends in Business and Tourism*, 2(3), pp. 79–83.
- Jahan, I., Karmakar, P., Hossain, M.M., Jahan, N. and Islam, M.Z. (2020) 'Fast food consumption and its impact on health', *Eastern Medical College Journal*, 5(1), pp. 28–36. Available at: <https://www.researchgate.net/publication/346220090> (Accessed: 3 November 2024).
- Jayasinghe, J.M.J.K. and De Silva, L.P.U. (2014) 'Fast food consumption and health status of students of a university in Sri Lanka', *Journal of Food and Agriculture*, 7(1–2), p. 38. <https://doi.org/10.4038/jfa.v7i1-2.5192>
- Jia, S.S., Wardak, S., Raeside, R. and Partridge, S.R. (2022) 'The impacts of junk food on health', *Frontiers for Young Minds*, 10. <https://doi.org/10.3389/frym.2022.694523>
- Kendall, E. (2023) 'Fast food', *Encyclopedia Britannica*, 1 September. Available at: <https://www.britannica.com/topic/fast-food> (Accessed: 3 November 2024).
- Keshari, P. and Mishra, C.P. (2016) 'Growing menace of fast food consumption in India: time to act', *International Journal of Community Medicine and Public Health*, 3(6), pp. 1355–1362. <https://doi.org/10.18203/2394-6040.ijcmph20161600>
- Ladeau, S.L. and Han, B.A. (2016) 'The emergence of disease ecology', *Japanese Journal of Zoo and Wildlife Medicine*, 21(3), pp. 53–58. <https://doi.org/10.5686/jjzwm.21.53>
- Mahmood, Y.N. and AbdulWahab, M.M. (2020) 'The impact of fast-food consumption on human health', *Diyala Agricultural Sciences Journal*, 12(2), pp. 25–32. <https://doi.org/10.52951/dasj.20120203>
- Man, C.S., Lim, K.H., Chan, Y.Y., Kee, C.C., Lim, K.K., Teh, C.H., Baharudin, A. and Abdul Aziz, N.S. (2021) 'Is fast food consumption a problem among adolescents in Malaysia?', *Journal of Health, Population and Nutrition*, 40, Article 31. <https://doi.org/10.1186/s41043-021-00254-x>
- Mayer, J.D. (1996) 'Social science, human ecology, and emerging diseases', *Social Science & Medicine*, 42(7), pp. 941–948. [https://doi.org/10.1016/0277-9536\(95\)00262-1](https://doi.org/10.1016/0277-9536(95)00262-1)
- Mubashshira, M.A.F. (2026) 'A Behavioral Geography Perspective on Socio-Demographic Factors Influencing Fast Food Consumption among Urban Dwellers: A Case Study of the Wattala–Mabola Urban Council', *Kolumpu Tamil E-Journal (KTEJ)*, 02(2), pp. 45–65. Available at: <https://arts.cmb.ac.lk/wp-content/uploads/2026/01/3.-Mubashshira.pdf>

- Nusrat, P. (2022) 'The trend of high consumption of fast foods and its impact on families, individuals, and societies', *AIJR Preprints*, (389), Version 1. <https://doi.org/10.21467/preprints.389>
- Oliveira, L. and Raposo, A. (2024) 'Factors that most influence the choice for fast food in a sample of higher education students in Portugal', *Nutrients*, 16(7), Article 1007. <https://doi.org/10.3390/nu16071007>
- Priyanath, H.M. and Dasanayaka, P.A.N.C. (2022) 'Impact of fast-food consumption on overweight among young adults in Sri Lanka', *International Journal of Education, Teaching, and Social Sciences*, 2(3), pp. 10–21. <https://doi.org/10.47747/ijets.v2i3.728>
- Rabotata, S. and Malatji, T.L. (2021) 'Factors influencing fast food consumption: A case study of University of Venda students, Limpopo, South Africa', *Technium Social Sciences Journal*, 26(1), pp. 888–899. <https://doi.org/10.47577/tssj.v26i1.5176>
- Saujan, I., Pathima Bushra, M.N. and Fathima Juhi, M.S. (2024) 'Fast-food consumption behaviour of undergraduates: With special reference to the state universities in Sri Lanka', *IRASS Journal of Arts, Humanities and Social Sciences*, 1(1), pp. 1–10.
- Singh, M. and Mishra, S. (2014) 'Effect of fast food consumption on the health of school-going children (9–13 years) in Lucknow district', *Indian Streams Research Journal*, 4(6). Available at: <https://www.isrj.net> (Accessed: 3 November 2024).
- Song, L.Z. (2023) 'Social impact of "take-out fast food" from the perspective of sociology', *Journal of Humanities and Social Sciences Studies*, 5(1), pp. 85–90. <https://doi.org/10.32996/jhsss.2023.5.1.12>
- Swaminathan, T.N. and Viswanathan, P.K. (2016) Drivers of consumer attitudes and their impact on fast food outlets in India. Great Lakes Institute of Management. Available at: <https://www.academia.edu/13648755> (Accessed: 3 November 2024).
- Wilcox, B.A. and Gubler, D.J. (2005) 'Disease ecology and the global emergence of zoonotic pathogens', *Environmental Health and Preventive Medicine*, 10(5), pp. 263–272. <https://doi.org/10.1265/ehpm.10.263>
- World Health Organization (2016) Nutrition, physical activity, and obesity: Fast food facts. Available at: <https://www.who.int> (Accessed: 3 November 2024).
- Yahya, F., Zafar, R. and Shafiq, S. (2013) 'Trend of fast food consumption and its effect on Pakistani society', *Food Science and Quality Management*, 11, pp. 1–9. Available at: <http://www.iiste.org> (Accessed: 3 November 2024).

ICRES26_015

**TECHNICAL ASSESSMENT OF WASTE-DERIVED PHASE CHANGE
MATERIALS (PCMS) FOR COLD STORAGE APPLICATIONS IN RURAL AREA****N. M. C. Jananjana*, S. M. Gamage, A. M. Wasantha***Department of Chemical and Process Engineering, Faculty of Engineering, University of Peradeniya***Correspondence E-mail: e20159@eng.pdn.ac.lk, TP: +94713219873*

Abstract: With the concept of sustainability, the increasing demand for sustainable thermal energy storage systems has enhanced research on alternative phase change materials (PCMs) derived from waste resources. Conventional synthetic polymer based commercial PCMs are often associated with high costs, limited availability, and negative environmental concerns, motivating the exploration of waste-derived PCMs as eco-friendly and economically viable substitutes. This literature review presents a comparative technical assessment of selected waste-derived PCMs for thermal energy storage applications using multi-criteria decision analysis (MCDM) using basic excel method and Visual PROMETHEE method. Key thermo-physical properties including melting temperature, latent heat of fusion, thermal conductivity, environmental impact and phase stability are analyzed based on experimental studies. PW-Sludge (Paraffin wax sludge from petroleum refinery waste), is the best-performing PCM (a value of 0.3825 in rankings) overall, demonstrating the ideal balance between thermal, environmental, and economic variables, according to both the Excel-based MCDM approach and the PROMETHEE results. CCO-FA (Fatty acids from waste coconut cooking oil) is the second most suitable material (a value of 0.2350 in rankings), followed by plant oil, W-SA, and WF-PCM. The conclusion that paraffin wax sludge is the most promising waste-based PCM among the alternatives under consideration is strengthened by the agreement between the two distinct decision-making techniques. By integrating experimental findings from previous studies with a multi-criteria evaluation perspective, this review seeks to identify the most promising waste-derived PCMs for sustainable low-temperature thermal energy storage. This review highlights the potential of waste-derived PCMs as sustainable alternatives for thermal energy storage and outlines future research directions for improving their reliability and scalability.

Keywords: Phase Change Materials; Bio-based PCMS; Waste-derived PCMS; Visual PROMETHEE; Organic PCMs

1. Introduction

The environmental impact of the energy sector remains a critical global concern due to greenhouse gas emissions and the increasing energy demand of modern societies. The need for thermal energy makes a substantial contribution to global warming, thus the creation of electric energy is not uniquely responsible for global warming (Maiorino *et al.*, 2025). Thermal Energy Storage (TES) systems have gained significant attention in this context, particularly those based on Phase Change Materials (PCMs), which can store and release large amounts of latent heat within a narrow temperature range. This characteristic makes them highly suitable for applications requiring stable thermal conditions, such as refrigeration systems, vaccine storage and transport, cold-chain food distribution, building cooling, and other temperature-controlled environments. PCMs are substances that can store and release thermal energy by changing their physical phase at a specific temperature. Recent studies have looked into waste-derived and bio-based PCMs as inexpensive and eco-friendly substitutes to overcome these constraints. Waste streams from petroleum refining, food processing, and agriculture present intriguing raw materials that could offer latent heat capacity and appropriate phase transition temperatures for cold storage applications. A thorough technical comparison of these waste-derived PCMs for rural cold storage is still lacking, despite increased interest. A life cycle assessment (LCA) analysis was carried out in the (Sarcinella *et al.*, 2025) project to determine whether the energy demand decrease provided by PCMs could balance the environmental impact related to their production (including the encapsulation procedure) and elimination. For sub-zero PCMs to be used effectively in Latent Cold Energy Storage (LCES) units at Domestic Refrigeration Systems Three distinct PCM types organic, inorganic and eutectic were compared in the study. The analysis's findings demonstrated that paraffin had the highest environmental impact, outperforming salt hydrates by 2.4 times and esters by 3 times (Sarcinella *et al.*, 2025). Based on these results, the study concluded that PCMs for sustainable applications should be made from materials derived from renewable resources, such as salt hydrates and esters, which are more environmentally friendly.

The main objective of this review is to identify the most suitable waste-derived PCM for cold storage applications (5-20°C) in rural areas. In order to do this, the study first examines the state of PCM technologies today and draws attention to the sustainability and technical drawbacks of traditional materials. The MCDM methodology is then used to assess a subset of waste-derived PCM candidates. The primary contribution of this work is the integration of technological, environmental, and economic factors into a cohesive decision-making framework, with a particular focus on waste-derived PCMs for rural cold storage, an area that has received limited attention in the literature.

2. PCM Categorization

Conventional synthetic PCMs in currently use can be divided into different categories according to well-known commercial examples: Bio-based, inorganic, organic, and eutectic PCMs. Each of these types has unique thermal and physical properties that affect its ability to store heat and suitability for various applications. Inorganic PCMs are composed of metallic and hydrated salts, whereas organic PCMs are primarily composed of carbon. Organic phase change materials (PCMs) generally exhibit low thermal conductivity, while possessing a relatively high enthalpy of fusion and strong chemical stability. (Bista *et al.*, 2018).

2.1 Organic PCMs

Fatty acids, certain esters, and paraffin are typical examples of organic PCMs. Due to their simplicity of use and thermal stability, organic PCMs are frequently used for a variety of applications, especially in energy storage systems and building materials. However, these materials are associated with certain environmental concerns; for example, some paraffin-based PCMs are derived from petroleum resources. In addition, they may present flammability risks under specific operating conditions. The environmental benefits of these materials are somewhat offset by the possibility of CO₂ emissions during production. Because of they can replace typical synthetic compounds with less impact on the environment, organic PCMs created from renewable sources are becoming more and more popular (Magendran *et al.*, 2019).

2.2 Inorganic PCMs

Inorganic PCMs, including salts, salt hydrates, and some low-melting metals, offer high energy storage capacity, superior thermal conductivity, and lower cost compared to organic PCMs (Bista et al., 2018). Common examples are sodium sulphate decahydrate ($\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$) and calcium chloride hexahydrate ($\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$), used in building, industrial, and solar thermal storage. They generally exhibit higher latent heat; however, they may demonstrate thermal instability over repeated cycles and possess corrosive properties (Sarcinella et al., 2025). Inorganic PCMs are particularly useful in applications requiring large latent heat, such as industrial processes and concentrated solar power (Cunha et al., 2023).

2.3 Eutectic PCMs

Eutectic PCMs can be either organic-organic, inorganic-inorganic, or a mix of organic and inorganic PCMs. Some of the drawbacks of pure organic or inorganic PCMs are addressed by these mixes. Unlike pure inorganic PCMs, which may experience phase separation, eutectic mixes do not experience segregation or phase separation during solidification. Compared to organic PCMs, eutectic PCMs can frequently provide a higher latent heat while retaining stable thermal characteristics. Eutectic PCMs are a very appealing choice for a variety of thermal management applications because of the ability to adjust their composition (Cunha et al., 2023). Some of the organic, inorganic PCMs and eutectic PCMs are listed with their melting temperatures and enthalpy of fusion, limitations in the following Table 1.

Table 1: List of organic, inorganic, eutectic PCMs

Type of PCM	Examples	Melting Point (°C)	Enthalpy of Fusion (kJ/kg)	Advantages	Limitations	References
Organic	<i>n</i> -Tetradecane	5.5	215	<ul style="list-style-type: none"> High thermal storage capability due to latent heat storage capacity 	<ul style="list-style-type: none"> Leakage possible in liquid phase without encapsulation Flammability risk in some organic PCMs (paraffins) Generally higher material cost Low thermal conductivity Some PCMs suffer from supercooling 	(Bista et al., 2018)
	Paraffin (C_{14})	5.5	228			
	Formic acid	8.4	247			
	<i>n</i> -Pentadecane	10	193.9	<ul style="list-style-type: none"> Thermal stability (maintain nearly constant temperature during phase change) 		
	Paraffin (C_{15})	10	205			
	Caprylic acid	16	150	<ul style="list-style-type: none"> Non-corrosive to containers and equipment 		
	Paraffin (C_{16})	16.7	237.1			
	Glycerine	17.9	198.7			
	Lactic acid	26	184	<ul style="list-style-type: none"> Available in a wide range of melting temperatures 		
<i>n</i> -Octadecane	28–28.1	245				
Inorganic	Hexadecane + tetradecane (2:3–0:1 by volume)	1.7 – 5.3	148.1 – 211.5	<ul style="list-style-type: none"> High latent heat per unit volume 	<ul style="list-style-type: none"> Supercooling problems 	(Bista et al., 2018)
	96% Tetradecane + 4% tetradecanol	5.5	206.4	<ul style="list-style-type: none"> Higher thermal conductivity than organic PCMs Relatively low cost and widely available Non-flammable 	<ul style="list-style-type: none"> Phase segregation during melting/freezing cycles Corrosive to common container materials Lower long-term cycling stability 	(Bista et al., 2018)
	Lauryl alcohol + caprylic acid (2:3 by quality)	6.2	173.2			
	45% capric acid + 55% lauric acid	17 – 21	143			
	Octadecane + docosane	25.5 – 27	203.8			
	31% Na_2SO_4 + 13% NaCl + 16% KCl + 40% H_2O	4	234			
	76% $\text{Na}_2\text{SO}_4 \cdot \text{H}_2\text{O}$	9.3	114.4			
$\text{Mn}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$ + $\text{MgCl}_2 \cdot 6\text{H}_2\text{O}$	25	130				
	H_2O	0	333	<ul style="list-style-type: none"> Sharp and well-defined melting point 	<ul style="list-style-type: none"> Preparation can be complex 	(Bista et al., 2018)
	$\text{LiClO}_3 \cdot 3\text{H}_2\text{O}$	8	155 – 253			

Eutectic	$\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$	18	254	<ul style="list-style-type: none"> • Customizable phase change temperature • Generally good thermal reliability • Reduced phase separation compared to single salt hydrates 	<ul style="list-style-type: none"> • Limited long-term property data • Possible component separation after many cycles (depending on system)
	$\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$	21	198		
	$\text{Mn}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$	25.8	125.8		
	$\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$	29	190.8		
	$\text{LiNO}_3 \cdot 3\text{H}_2\text{O}$	30	296		

3. Sustainable PCM Alternatives

In order to lessen the environmental impact of all applications in which they are utilized, PCMs with "sustainability" features are becoming more and more significant. Compared to commercial synthetic PCMs, sustainable PCMs have a lower environmental impact due to their composition or production method. As bio-based PCMs come from renewable biological sources rather than fossil fuels, they are a sustainable class of organic phase change materials. They are often non-toxic, eco-friendly, and frequently biodegradable, these materials have a smaller environmental impact during manufacturing, use, and disposal. The fact that many bio-PCMs may be obtained from industrial by-products or agricultural leftovers offers an additional sustainability benefit by lowering the cost of raw materials and increasing the value of waste streams. Waste vegetable oils, animal fats, fatty acid derivatives, and other food and pharmaceutical industry by-products are a few examples of materials that can show appropriate latent heat and melting temperatures for thermal energy storage applications

In addition to their advantages for the environment, bio-based PCMs support circular economy initiatives by transforming low-value waste into useful thermal storage materials. They offer comparatively steady phase change behavior and strong compatibility with building and packaging materials due to their chemical composition, which is frequently rich in fatty acids and esters. Additionally, due to their reduced toxicity, they are safer to employ in consumer product thermal management, cold-chain transportation, and indoor temperature regulation. Ongoing research focuses on improving the thermal conductivity, oxidative stability, and long-term durability of these materials through encapsulation and composite formation, thereby enhancing their potential as environmentally friendly alternatives to conventional petroleum-based phase change materials (PCMs).

3.1 Bio-based PCMs

Bio-based phase change materials (PCMs) are thermal energy storage materials derived from renewable biological sources such as plant oils, animal fats, esters, and polyols and agricultural by-products (Sarcinella *et al.*, 2025). The reasons of their low toxicity, biodegradability, and renewable source, bio-based PCMs are sustainable organic phase-change materials. They can also be made from food processing and agricultural waste, which lessens the impact on the environment. Animal fats, waste vegetable oils, and several pharmaceutical by-products have demonstrated promise as PCMs. The types of bio-based PCMs are shown in Figure 1

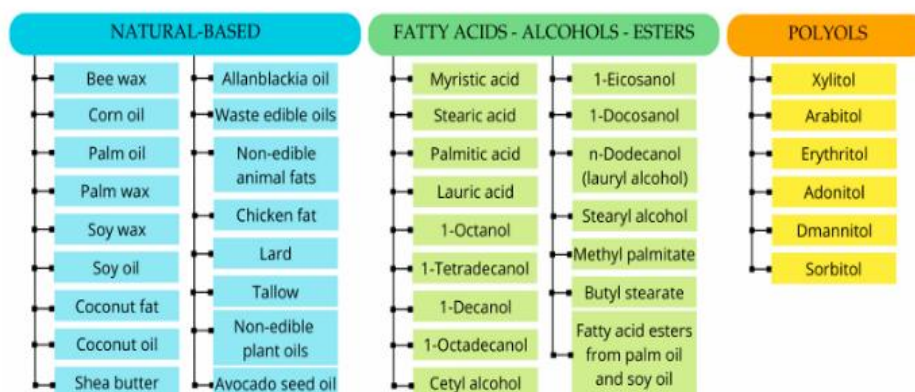


Figure 1: Bio-based organic PCMs organized into categories (Sarcinella *et al.*, 2025)

In order to enhance the thermal characteristics of the original bio-based PCM, these PCMs can also be used to create eutectic mixes such palmitic acid–stearic acid, myristic acid–capric acid, and palmitic acid–capric acid (Benhorma *et al.*, 2024). Bio-based organic PCMs represent one of the most promising sustainable options in this context These materials have the extra advantage of being biodegradable since they are made from renewable resources including fatty acids, natural waxes, and biopolymers. As a result, they provide a more sustainable energy storage option and follow the expanding trend of eco-friendly technologies(Sarcinella *et al.*, 2025).

3.2 Waste-derived PCMs

The sustainable thermal energy storage materials known as waste-derived phase change materials (PCMs) are made from industrial, food, and agricultural waste streams rather than virgin resources. Used cooking oil, waste vegetable oils, animal fats, fatty acid leftovers, biodiesel byproducts, paraffin sludge, and wax waste are common sources. By transforming low-value waste into valuable heat storage media and lowering disposal issues and environmental contamination, these materials promote the ideas of the circular economy. According to Manikandan, Devarajan, and Vickram (2025), waste-derived PCMs are often divided into three categories: food waste, agricultural waste, and industrial by-product(Manikandan, Devarajan and Vickram, 2025). Coconut-based PCMs were examined, using a simple physical blending method to produce an inexpensive, eco-friendly, and high-performing bioSSPCM, using abundant and easily obtained materials(Muchtar *et al.*, 2022). Initially the PCM material is heated using a heater for 10 minutes about 80 °C. And then add the activated carbon sample to PCM and mix it well for 10 minutes. Finally let the sample to cool down in a ice bath. This method can simply figure out as follows in Figure 2.

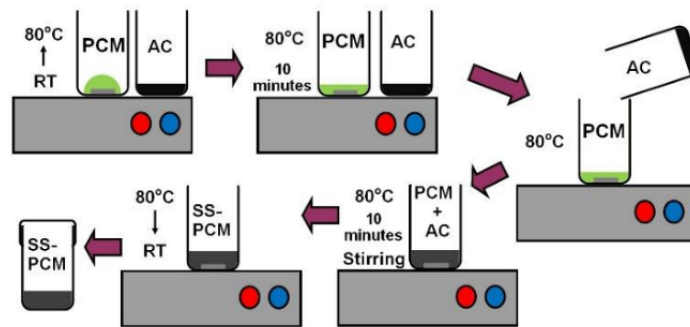


Figure 2: Simple physical blending synthesis of shape stabilized phase change materials(Muchtar *et al.*, 2022)

4. Selected Waste-derived PCMs for MCDM Analysis

Five waste-derived PCMs for MCDM analysis are selected as they are the most technically feasible, widely available, and already researched for thermal energy storage. They are CCO-FA – Fatty acids from waste coconut cooking oil, WF-PCM – Processed waste animal fat, W-SA – Waste stearic acid, PW-Sludge – Paraffin wax sludge (petroleum refinery waste), Plant oils – Palm oil / Sunflower oil (waste or low-grade). Physical Properties of Selected Waste-Derived PCMs in Table 2.

Table 2: Basic Physical Properties of Selected Waste-Derived PCMs

Property / Parameter	CCO-FA	WF-PCM	W-SA	PW-Sludge	Plant Oil
Source type	Waste cooking oil + fatty acids	Waste fats/waxes	Waste stearic acid	Petroleum wax sludge	Waste plant-based oil
Physical state (at room temperature)	liquid	liquid	liquid	Solid	liquid
Phase change temperature (°C)	23-25	30-55	60-75	5.5-10	33-40
Latent heat of fusion (kJ/kg)	115.7	57	198-288	180-230	95.5
Density (kg/m ³)	850-900	880-920	940-960	900-950	880-910
Thermal conductivity (W/m·K)	0.115	0.10-0.20	0.10-0.20	0.20-0.40	0.10-0.20
Volume change on melting (%)	Low-moderate	Moderate	Low	Low	Moderate

Thermal stability (cycles)	Moderate	Moderate	High	High	Moderate
Biodegradability	High	Moderate	High	Low	High
Corrosiveness	Low	Low	Very low	Low–moderate	Very low

5. Evaluation Criteria

This review considers nine key criteria for evaluating waste-derived PCMs for potential use as phase change materials.

5.1 Ability to Undergo Phase Change within Required Temperature Range

Melting temperatures for organic PCMs, including paraffins and fatty acids, are dependent on their molecular structure. According to Bista et al. (2018), paraffins such as n-tetradecane and n-pentadecane melt at 5.5 °C and 10 °C, respectively. According to Irsyad et al. (2023), stearic acid (71.21 °C; 288.39 J/g) and palmitic acid (66.9 °C; 244.2 J/g) have better latent heat storage capacity and greater phase change temperatures. Fatty acids produced from CCO exhibit a melting range of 8.2–25.3 °C (Irsyad et al., 2023). The melting behavior of animal fats varies greatly; isolated animal fatty acids may melt at about 32 °C, while raw tallow usually melts at 40–50 °C (Sarcinella et al., 2025).

5.2 High Latent Heat Storage Capacity per Unit Mass

Fatty acids and paraffin waxes are examples of organic PCMs that are appropriate for thermal energy storage due to their large latent heat capacities. Among organic PCMs, stearic acid has a latent heat of about 198–288 kJ/kg when it is pure (Zayed et al., 2025). A lower latent heat of roughly 115.7 kJ/kg is displayed by fatty acids produced from CCO (Irsyad et al., 2023). The latent heat of fusion of commercial-grade paraffin wax usually ranges from 166 to 214.4 kJ/kg, with average values being between 180 and 230 kJ/kg. According to Lawer-Yolar, Dawson-Andoh, and Atta-Obeng (2019), palm kernel oil has a lower latent heat of crystallization, at roughly 95.5 kJ/kg.

5.3 Capability to Transfer Heat Effectively (Intrinsic Thermal Conductivity)

Organic PCMs intrinsically have relatively low thermal conductivity values. Organic PCMs (paraffin & fatty acids) have inherently low conductivity ~0.14–0.8 W/m·K common across these candidates (R et al., 2025). Bio PCM -thermal conductivity (κ) of bio-PCMs is about 0.1–0.2 W/m.K (Zadshir, Kim and Yin, 2024). The WCCO is also very interesting to be developed as thermal energy storages considering the similarities it has with CCO such as the 0.155 W/m.K thermal conductivity.

5.4 Thermal and Chemical Stability Over Repeated Melting/Freezing Cycles

Fatty acid- By monitoring weight variations over time as the temperature rises, thermogravimetric analysis (TGA) was utilized to evaluate the PCMs' thermal stability and investigate the amounts of their volatile components. Figure shows that 0.025 g of free fatty acids (FFAs) and 0.043 g of fatty acid methyl ester (FAME) were heated from room temperature to 550 °C at a rate of 10 °C/min while staying below the Tzero aluminum pan's softening point. Up to roughly 110 °C, there was no discernible weight loss, indicating that neither the FFAs nor the FAME contained moisture following processing (Zadshir, Kim and Yin, 2024).

5.5 Resistance to Leakage During Liquid Phase Without Complex Containmentment

Mixed fats may have even broader liquefaction and more leakages. Oils liquefy fully at low T significant leak risk without containment (Herrera, De la Hoz Siegler and Clarke, 2024). Paraffin wax shows strong cycling stability with minimal change. Pure stearic transitions are sharper, reducing leakage volume (Zayed et al., 2025)

5.6 Non-Corrosive Behavior and Compatibility with Container Materials

Paraffins and fatty acids are examples of organic PCMs that are generally non-corrosive to common metallic and non-metallic. Fatty acids are non-corrosive to metals like stainless steel when pure. Stearic acid (pure) is non corrosive in typical PCM uses (Zayed et al., 2025). Oils can react with some polymers, but generally mild (Zadshir, Kim and Yin, 2024).

5.7 Availability and Consistency of Waste Raw Material Supply

Fatty acids from used cooking oil or refined refinery wax streams are examples of waste-derived organic PCM possibilities with differing levels of supply consistency. These feedstocks can be easily found in areas with a lot of leftover cooking fats and oils, albeit their quality may differ. Similar consistency can be achieved in industrial settings with waste refinery wax or sludge supplies; however this depends on processing outputs. Uniform commercial PCM supplies, on the other hand, are managed but not waste-derived.

5.8. Low Environmental Impact and Good Biodegradability

Compared to materials that are solely sourced from petroleum, organic PCMs based on bio-derived waste streams (such as leftover cooking fats) naturally have a lower environmental effect and higher biodegradability. When utilized as PCM, organic fatty acids and feedstocks sourced from plants are less hazardous and more biodegradable, supporting sustainability objectives. Although petroleum-derived paraffin is stable and efficient, it is a fossil-derived substance with related environmental concerns.

5.9 Low Processing and Purification Cost for PCM Preparation

Converting waste feedstock's into useful PCMs has varying costs. Usable organic PCM fractions can be obtained via rather straightforward purification and fractionation of certain waste fats or oils. Costs increase with more involved processing, such as fractionating, mixing into eutectics, refining, or creating composites.

6. Technical Assessment of Waste-Derived Phase Change Materials

The increasing potential of bio-based and waste-derived phase change materials (PCMs) as environmentally friendly substitutes for traditional synthetic thermal energy storage materials is highlighted in this analysis. Finding the best waste-derived PCM is the aim of this investigation. A methodical, quantitative approach called Multi-Criteria Decision Making (MCDM) is used to rank and assess options when there are several, frequently contradictory criteria. By using a decision matrix, it makes data-driven, objective decision-making possible (Rikalovic and Cosic, 2014). Following Table 3 shows the evaluation criteria, relative weights (0–1 scale) are awarded based on their significance, as established by basic research and literature.

Table 3: Weighting scale

Criteria	Value
Very good	5
Good	4
Average	3
Bad	2
Very bad	1

The Table 4 summarizes the criteria and corresponding weights used in the MCDM analysis to evaluate best waste-based phase change materials, reflecting their relative importance in achieving effective, sustainable, and economically viable thermal energy storage.

Table 4: Weight assigning for selected criteria

No.	Criteria	Weight	Justification for Assigned Weight
1	Ability to undergo phase change within the required application temperature	0.17	This criterion was given the highest weight because matching the phase change temperature with the target application (5-20 ⁰ C) is essential for effective thermal energy storage performance.
2	High latent heat storage capacity per unit mass	0.15	A high latent heat capacity directly determines the amount of energy stored, making it a critical factor for efficient PCM utilization.
3	Capability to transfer heat effectively (intrinsic thermal conductivity)	0.09	Thermal conductivity affects charging and discharging rates but can be enhanced using additives, so it was assigned a moderate weight.

4	Thermal and chemical stability over repeated melting/freezing cycles	0.10	Long-term stability is important to ensure durability and consistent performance over multiple thermal cycles.
5	Resistance to leakage during liquid phase without complex containment	0.08	Leakage resistance is important for system reliability, but engineering solutions can partially mitigate this issue.
6	Non-corrosive behavior and compatibility with common container materials	0.10	Compatibility with containers prevents material degradation and maintenance issues, justifying a moderate weight.
7	Availability and consistency of waste raw material supply	0.12	A reliable and consistent waste supply is crucial for large-scale and sustainable PCM production.
8	Low environmental impact and good biodegradability	0.13	Environmental sustainability is a key motivation for using waste-based PCMs, warranting a relatively high weight.
9	Low processing and purification cost for PCM preparation	0.06	Although cost is important, it was assigned a lower weight because processing methods can be optimized over time.

6.1 Method One: Simple Multi-Criteria Decision Analysis using Excel

A multi-criteria Decision matrix was used to determine the best waste-derived PCM, using excel calculation. Here are the considered criteria for decision making. Nine PCM performance-related technical, environmental, and economic criteria were considered in Table 5.

Table 5: Simple Multi-Criteria Decision Analysis using Excel

Criteria to be considered	Weight (1-5)	Score					Weighted score				
		CCO-FA	WF-PCM	W-SA	PW-Sludge	Plant oil	CCO-FA	WF-PCM	W-SA	PW-Sludge	Plant oil
1. Ability to undergo phase change within the required application temperature range(Melting Temp Suitability)	0.17	4	3	2	4	4	0.68	0.51	0.34	0.68	0.68
2. High latent heat storage capacity per unit mass	0.15	3	1	4	5	2	0.45	0.15	0.6	0.75	0.3
3. Capability to transfer heat effectively (intrinsic thermal conductivity)	0.09	2	2	2	3	2	0.18	0.18	0.18	0.27	0.18
4. Thermal and chemical stability over repeated melting/freezing cycles	0.1	3	3	5	4	4	0.3	0.3	0.5	0.4	0.4
5. Resistance to leakage during liquid phase without complex containment	0.08	3	2	4	4	1	0.24	0.16	0.32	0.32	0.08
6. Non-corrosive behavior and compatibility with common container materials	0.1	4	3	4	4	3	0.4	0.3	0.4	0.4	0.3
7. Availability and consistency of waste raw material supply	0.12	4	3	3	4	4	0.48	0.36	0.36	0.48	0.48
8. Low environmental impact and good biodegradability	0.13	5	3	4	2	5	0.65	0.39	0.52	0.26	0.65
9. Low processing and purification cost for PCM preparation	0.06	4	3	3	5	5	0.24	0.18	0.18	0.3	0.3
Total(out of 5)	1					Total	3.62	2.53	3.4	3.86	3.37

6.2 Method Two: Simple Multi-Criteria Decision Analysis using Visual PROMETHEE

In addition to the weighted scoring approach, also applied the method using Visual PROMETHEE software to rank the same five waste-derived PCMs as in Figure 3.

Scenario1	Melting temp...	Latent heat ...	Thermal con...	Thermal stab...	Resistance t...	Non corrosive	Availability	Low environ...	Low cost
Unit	unit	KJ/Kg	W/m.K	unit	unit	unit	unit	unit	unit
Cluster/Group	◆	◆	◆	◆	◆	◆	◆	◆	◆
Preferences									
Min/Max	max	max	max	max	max	min	max	max	min
Weight	0,17	0,15	0,09	0,10	0,08	0,10	0,12	0,13	0,06
Preference Fn.	Usual	Usual	Usual	Usual	Usual	Usual	Usual	Usual	Usual
Thresholds	absolute	absolute	absolute	absolute	absolute	absolute	absolute	absolute	absolute
- Q: Indifference	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
- P: Preference	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
- S: Gaussian	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Statistics									
Minimum	2,00	57,00	0,10	2,00	1,00	3,00	3,00	3,00	3,00
Maximum	4,00	214,40	0,20	4,00	4,00	4,00	4,00	5,00	5,00
Average	3,40	136,12	0,16	3,00	2,80	3,80	3,40	3,80	4,00
Standard Dev.	0,80	60,47	0,03	0,89	1,17	0,40	0,49	0,75	0,89
Evaluations									
CCO-FA	4,00	115,70	0,15	3,00	3,00	4,00	4,00	5,00	4,00
WF-PCM	3,00	57,00	0,10	2,00	2,00	3,00	3,00	3,00	3,00
W-SA	2,00	198,00	0,17	4,00	4,00	4,00	3,00	4,00	3,00
PW-Sludge	4,00	214,40	0,20	4,00	4,00	4,00	4,00	3,00	5,00
Plant oil	4,00	95,50	0,16	2,00	1,00	4,00	3,00	4,00	5,00

Figure 3: MCDM analysis using Visual PROMETHEE software

7. Results and Discussion

According to above criteria the Excel-based MCDM technique and the PROMETHEE results agree that PW-Sludge is the highest-performing PCM overall, exhibiting the optimal balance between thermal, environmental, and economic factors. The second most appropriate substance is CCO-FA, which is followed by W-SA, WF-PCM, and plant oil. The conclusion that paraffin wax sludge is the most promising waste-based PCM among the alternatives under consideration is strengthened by the agreement between the two distinct decision-making techniques. PROMETHEE ranking chart is shown in Figure 4.

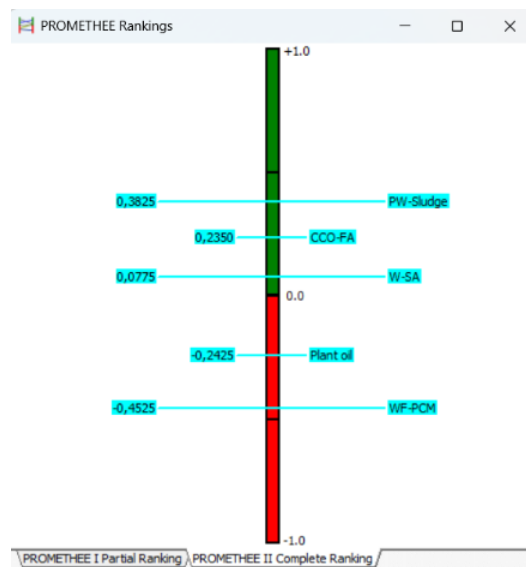


Figure 4: PROMETHEE ranking chart

The selection of PW-Sludge as the most suitable waste-derived PCM is supported by the quantitative results obtained from both the Excel-based and the Visual PROMETHEE analysis. In the weighted scoring method, PW-Sludge achieved the highest total score of 3.86,

indicating superior overall performance among the evaluated alternatives. This high ranking is primarily attributed to its suitable phase change temperature (5.5–10 °C) within the target cold storage range of 5–20 °C, high latent heat capacity (180–230 kJ kg⁻¹), relatively higher thermal conductivity (0.20–0.40 W m⁻¹ K⁻¹) compared with other organic PCMs, and good thermal stability during repeated melting and solidification cycles. In addition, PW-Sludge benefits from low processing cost and consistent availability as a refinery waste stream, which improves its practical applicability in rural cold storage systems. In comparison, CCO-FA ranked second, with a lower preference score (0.2350) and a slightly lower weighted score due to its moderate latent heat capacity (115.7 kJ kg⁻¹) and lower thermal conductivity, despite its advantage of high biodegradability and lower environmental impact.

8. Conclusion

The suitability of a number of waste-derived phase change materials (PCMs) for cold storage applications in rural areas, where affordability, accessibility, thermal stability, and environmental safety are particularly crucial was examined in this review. Two separate Multi-Criteria Decision Making (MCDM) techniques were used; the Visual PROMETHEE outranking method and an Excel-based weighted scoring method. Both methods assessed the PCMs based on important thermal, physical, environmental, and economic criteria, giving more weight to characteristics that directly affect cold storage performance, such as phase change temperature suitability, latent heat capacity, and thermal stability, while still taking compatibility, processing cost, environmental impact, and material availability into consideration. Both methods produced consistent results, identifying paraffin wax sludge (PW-Sludge) as the most suitable PCM due to its balanced thermal performance, stability, and low cost. Coconut cooking oil-derived fatty acids (CCO-FA) ranked second, offering a more environmentally friendly bio-based alternative. The results between methods strengthens the reliability of these findings for low-cost rural thermal energy storage applications

References

- Benhorma, A. et al. (2024) 'Prospects and challenges of bio-based phase change materials: An up to date review', *Journal of Energy Storage*, 90, p. 111713. Available at: <https://doi.org/https://doi.org/10.1016/j.est.2024.111713>.
- Bista, S. et al. (2018) 'Performance improvement and energy consumption reduction in refrigeration systems using phase change material (PCM)', *Applied Thermal Engineering*, 142(April), pp. 723–735. Available at: <https://doi.org/10.1016/j.applthermaleng.2018.07.068>.
- Cunha, S. et al. (2023) 'Perspective on the Development of Energy Storage Technology Using Phase Change Materials in the Construction Industry: A Review', *Energies*, p. 4806. Available at: <https://doi.org/10.3390/en16124806>.
- Herrera, P., De la Hoz Siegler, H. and Clarke, M. (2024) 'Fatty Acids as Phase Change Materials for Building Applications: Drawbacks and Future Developments', *Energies*, p. 4880. Available at: <https://doi.org/10.3390/en17194880>.
- Lawer-Yolar, G., Dawson-Andoh, B. and Atta-Obeng, E. (2019) 'Novel phase change materials for thermal energy storage: Evaluation of tropical tree fruit oils', *Biotechnology Reports*, 24, p. e00359. Available at: <https://doi.org/https://doi.org/10.1016/j.btre.2019.e00359>.
- Magendran, S.S. et al. (2019) 'Synthesis of organic phase change materials (PCM) for energy storage applications: A review', *Nano-Structures & Nano-Objects*, 20, p. 100399. Available at: <https://doi.org/https://doi.org/10.1016/j.nanoso.2019.100399>.
- Maiorino, A. et al. (2025) 'Achieving off-grid refrigeration in remote areas : A solar-powered vapor compression refrigerator prototype with PCM integration', *International Journal of Refrigeration*, 169(September 2024), pp. 267–278. Available at: <https://doi.org/10.1016/j.ijrefrig.2024.10.028>.
- Mannik andan, S., Devarajan, Y. and Vickram, S. (2025). Advancing Thermal Energy Storage with Industrial and Agricultural Waste-Derived Phase Change Materials: A Path Towards Sustainable Energy Systems. *Process Safety and Environmental Protection*, p.107068. doi:<https://doi.org/10.1016/j.psep.2025.107068>
- Marques D., Martins, N. and Neto, F. (2025). Powering the future: Releasing the potential of phase change materials in domestic refrigeration systems to store renewable energy. *Applied Thermal Engineering*, [online] 264, p.125421. doi:<https://doi.org/10.1016/j.applthermaleng.2025.125421>
- Muchtar, A.R. et al. (2022) 'Shape-Stabilized Phase Change Materials : Performance of Simple Physical Blending Synthesis and the Potential of Coconut Based Materials To cite this version : HAL Id : hal-03689127'.
- Irsyad, M., Amrizal, Harmen, Amrul, Susila Es, M.D. and Diva Putra, A.R.(2023). Experimental study of the thermal properties of waste cooking oil applied as thermal energy storage. *Results in Engineering*, [online]18,p.101080. doi:<https://doi.org/10.1016/j.rineng.2023.101080>
- R, B. et al. (2025) 'Advancements in paraffin wax phase change materials: A comprehensive review of enhancement techniques and thermal storage applications', *Thermochimica Acta*, 753, p. 180129. Available at: <https://doi.org/https://doi.org/10.1016/j.tca.2025.180129>.
- Sarcinella, A. et al. (2025) 'Sustainable Organic Phase Change Materials for Sustainable Energy Efficiency Solutions', pp. 1–22.
- Zadshir, M., Kim, B.-W. and Yin, H. (2024) 'Bio-Based Phase Change Materials for Sustainable Development', *Materials*, p. 4816. Available at: <https://doi.org/10.3390/ma17194816>.
- Zayed, M. et al. (2025) 'Development of bio-based phase change material composites for thermal regulation of cotton fabrics', *Discover Chemistry*, 2(1), p. 271. Available at: <https://doi.org/10.1007/s44371-025-00353-2>



ICRES26_021

CIRCULAR ECONOMY PRINCIPLES FOR ADAPTIVE REUSE OF COLONIAL BUILDINGS OF WORLD HERITAGE SITE: CASE STUDIES OF GALLE FORT

K.B. Seenapatabendige^{1*}, R. U. Halwatura², M. Kariyakarawana¹

¹*Department of Architecture, Faculty of Built Environment and Spatial Science, Southern Campus, General Sir John Kotelawala Defence University, Kiribbanwewa, Sooriyawewa, Sri Lanka.*

²*Department of Civil Engineering, University of Moratuwa, Sri Lanka*

**Correspondence E-mail: kbseenapatabendige@gmail.com, TP: +94716190312*

Abstract: The adaptive reuse of cultural heritage buildings is increasingly recognised as a key strategy for promoting sustainability within the built environment. In World Heritage Sites, where redevelopment pressures coexist with strict conservation requirements, adaptive reuse presents an opportunity to extend building life cycles while safeguarding cultural value. This study investigates the application of circular economy (CE) principles in the adaptive reuse of colonial buildings within Galle Fort, Sri Lanka, a living World Heritage Site characterised by intensive tourism activity and climatic exposure. The research adopts a mixed-methods approach combining transect walks, spatial mapping, stakeholder consultations, in-depth interviews, and a life-cycle-based assessment framework. Six colonial building typologies; Dutch townhouses, row houses, courtyard houses, shop houses, service quarters, and British bungalows were analysed using a five-point rating scale across five life-cycle stages: design, manufacture and supply, construction, in-use and refurbishment, and end of life. The assessment evaluates circular economy criteria including adaptability, design for disassembly, material optimisation, fabric retention, operational durability, and material recovery potential. Findings indicate that Dutch townhouses and courtyard houses exhibit the highest circular economy performance due to their adaptable spatial layouts, durable traditional materials, and capacity for reversible interventions. British bungalows demonstrate balanced circular potential, while row houses, shop houses, and service quarters show moderate to lower performance, constrained by spatial limitations and functional rigidity. Circular strategies are most effectively implemented during early life-cycle stages, particularly design and construction, whereas end-of-life circularity remains limited due to heritage conservation constraints. The study contributes a context-specific circular economy framework tailored to colonial heritage buildings in tropical coastal settings. By bridging global CE principles with local heritage realities, the research offers practical insights for sustainable heritage-led urban regeneration in World Heritage Sites.

Keywords: Adaptive reuse; Circular economy; Colonial heritage buildings; Galle Fort

1. Introduction

Rapid urbanization, climate change, and increasing resource scarcity have intensified the need for environmentally sustainable approaches within the built environment (Pomponi & Moncaster, 2017). In this context, existing buildings play a critical role in achieving sustainability objectives, as they embody substantial material, energy, and cultural value (Bullen & Love, 2011). Among these, cultural heritage buildings are of particular importance due to their historic significance, architectural character, and contribution to social identity (Pendlebury, 2013). However, many heritage buildings remain underutilized or face pressure from redevelopment, especially in historic urban areas influenced by tourism and economic transformation (Girard & Gravagnuolo, 2018). Heritage buildings located within World Heritage Sites constitute irreplaceable cultural assets while also embodying substantial material, energy and historical value. The adaptive reuse of such buildings has emerged as a critical strategy for promoting sustainable development, as it extends building life cycles, reduces demolition-related waste, conserves embodied energy and mitigates environmental impacts associated with new construction (Bullen & Love, 2011; Foster, 2020). From a circular economy (CE) perspective, adaptive reuse supports core principles such as material retention, resource efficiency, value preservation and the reduction of virgin material consumption, while safeguarding cultural significance (Pomponi & Moncaster, 2017; Girard & Gravagnuolo, 2018). Colonial-era buildings represent a distinct category of cultural heritage, particularly in post-colonial contexts such as Sri Lanka (Amarathunga, 2011). These buildings are not only physical artifacts of history but also key components of urban form, place identity, and economic activity. In World Heritage Sites such as Galle Fort, colonial buildings are increasingly subjected to adaptive reuse for tourism, commercial, and hospitality functions (Karun et al., 2017). While adaptive reuse is widely recognized as a means of preserving heritage value and extending building life cycles, its environmental performance is often assumed rather than systematically evaluated (Owojori & Kim, 2018).

The circular economy (CE) has emerged as an important framework for addressing sustainability challenges by reducing resource extraction, minimizing waste generation, and extending the useful life of materials and buildings. Unlike the conventional linear model of construction and consumption, which follows a “take–make–dispose” approach, the circular economy promotes strategies such as material reuse, life-cycle extension, resource efficiency, and regenerative design (Debacker & Manshoven, 2016). Although CE principles have been widely explored in relation to new construction and industrial production systems, their application within cultural heritage conservation and adaptive reuse remains relatively limited and is often discussed at a conceptual level (Nocca, 2017; Foster, 2020). Existing studies on circular economy strategies for the adaptive reuse of cultural heritage buildings primarily focus on global or theoretical frameworks, emphasizing life-cycle thinking and material circularity (Pomponi & Moncaster, 2017; Girard & Gravagnuolo, 2018). While these studies highlight the environmental benefits of reuse-oriented approaches, they frequently lack context-specific analysis, particularly in relation to heritage buildings located within World Heritage Sites. Such sites operate under strict conservation regulations and face complex challenges, including climate exposure, intensive tourism activities, and the need for long-term preservation. These contextual factors are often insufficiently addressed in the current literature on CE-based adaptive reuse.

Galle Fort, a UNESCO World Heritage Site in Sri Lanka, contains a dense concentration of colonial-era buildings that have been adaptively reused for tourism-related functions such as boutique hotels, villas, restaurants, cafés, craft shops, and jewellery stores, creating a distinctive heritage-based tourism landscape (Indika, 2020). Previous studies in Sri Lanka indicate that adaptive reuse in heritage contexts contributes to tourism attractiveness, economic revitalization, and improved user experiences, particularly within hospitality-oriented heritage buildings (Amarathunga, 2011; Karun et al., 2017). Empirical findings further suggest that adaptive reuse supports resource conservation, prevents construction waste, and enables the preservation of culturally and economically valuable historic structures. In response to these gaps, this study aims to contextualize global circular economy frameworks within the local setting of Galle Fort and examine how circular economy strategies are implemented in the adaptive reuse of colonial heritage buildings (Girard & Gravagnuolo, 2018; Foster,

2020). By analysing selected case studies, the research evaluates the environmental, social, and economic implications of circular adaptive reuse practices. Through this investigation, the study seeks to develop a localized and practice-oriented framework that can support sustainable heritage management in tropical coastal World Heritage Sites. Specific objectives were **to adapt and contextualize global circular economy frameworks** into a locally appropriate framework, identify circular business model, for the adaptive reuse of colonial heritage buildings within the World Heritage Site of Galle Fort, Sri Lanka, **to examine adaptive reuse practices through a circular economy lens**, identifying how circular economy strategies are integrated into the reuse of colonial buildings.

a. Adaptive reuse of colonial buildings: A circular business model

The reviewed literature highlights the growing recognition of adaptive reuse as an effective strategy for extending the lifespan of buildings and promoting urban sustainability. Studies examining Galle Fort and similar heritage contexts mainly focus on issues such as conservation ethics, development pressures, and governance challenges. However, these studies provide limited discussion on environmental performance or the integration of circular economy (CE) principles within adaptive reuse practices (Amarathunga, 2011; Indika, 2020). Research conducted in countries such as Australia, Europe, and the United States further demonstrates the environmental and functional advantages of adaptive reuse. Nevertheless, in many of these studies, circular economy strategies are addressed only indirectly, without being explicitly framed within comprehensive life-cycle or circularity-based frameworks (Bullen & Love, 2011; Owojori & Kim, 2018). Conceptual studies advance CE thinking in the built environment by highlighting material reuse, adaptability, and design-for-disassembly, yet these frameworks are rarely operationalised in protected heritage buildings or tourism-driven reuse contexts (Pomponi & Moncaster, 2017; Foster, 2020). European initiatives such as the CLIC project and related scholarship position cultural heritage as a circular urban resource but lack empirical validation in tropical, coastal World Heritage Sites (Girard & Gravagnuolo, 2018; CLIC, 2019). Overall, the literature reveals a gap between CE theory and applied heritage adaptive reuse, particularly within colonial building typologies in Global South contexts. Results of comparative evaluation of published research highlighted the key focus areas.

Table 1: Comparative evaluation matrix of the literature review

No.	Author(s)	Year / Context	Circular Economy Focus	Heritage / Adaptive Reuse Focus	Methodological Strength	Policy / Planning Relevance
1	Girard & Gravagnuolo	2018 / EU	●	●	●	●
2	Foster	2020 / Global	●	●	●	●
3	Pomponi & Moncaster	2017 / Global	●	●	●	●
4	Bullen & Love	2011 / Australia	●	●	●	●
5	Conejos et al.	2016 / Australia	●	●	●	●
6	Debacker & Manshoven	2016 / EU	●	●	●	●
7	Nocca	2017 / Italy	●	●	●	●
8	Karun et al.	2017 / Malaysia	●	●	●	●
9	Amarathunga	2011 / Sri Lanka (Galle Fort)	●	●	●	●
10	Indika	2020 / Sri Lanka (Galle Fort)	●	●	●	●
11	CLIC Project (H2020)	2019 / EU	●	●	●	●

- = Strong
- = Moderate
- = Limited

b. Conceptual framework

Figure 1 illustrates the conceptual relationship between colonial buildings, adaptive reuse, and circular economy-oriented business model within the context of Galle Fort, a living world heritage site. The diagram illustrates how colonial-era buildings are transformed through adaptive reuse into tourism-related functions such as villas, cafés, restaurants, and retail spaces. This transformation process is influenced by two key factors: policy regulations and innovation-driven interventions. Regulatory frameworks play an important role in ensuring that redevelopment activities comply with heritage conservation guidelines and planning regulations. At the same time, innovations in construction techniques, material selection, reversibility, and spatial reconfiguration support the integration of circular economy principles within reuse practices. In this context, adaptive reuse acts as a transitional

mechanism that links heritage conservation objectives with circular economic practices. Through this process, buildings can achieve extended life cycles, improved resource efficiency, and continued economic value while maintaining the cultural integrity of a protected World Heritage Site.

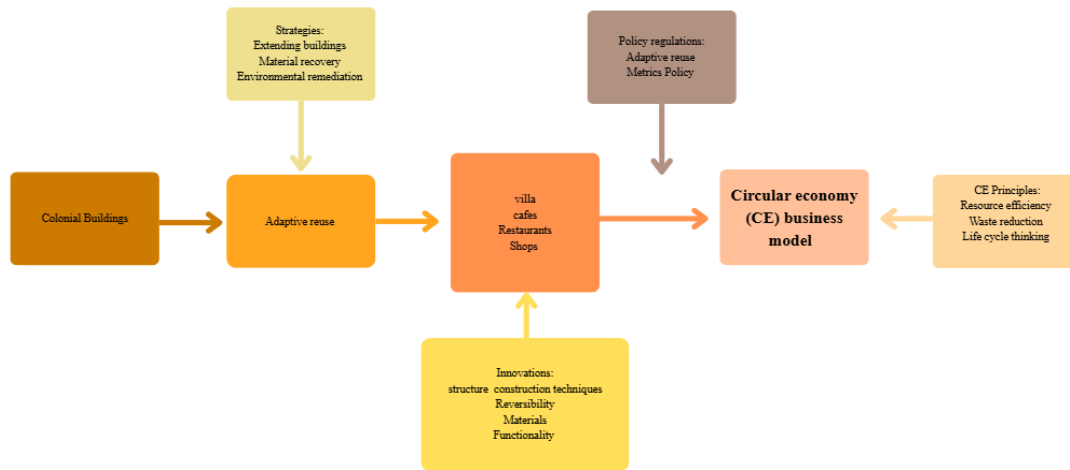


Figure 1: Conceptual Framework

2. Methodology

This study adopts a mixed-methods approach to examine the adaptive reuse of colonial buildings in Galle Fort from a circular economy perspective. Data were collected through several qualitative and spatial research methods, including transect walks, market mapping, in-depth interviews with selected building owners, and stakeholder consultations. The study sample consisted of six types of colonial buildings identified within the study area: Dutch townhouses (10), row houses (5), courtyard houses (15), shop houses (10), service quarters, and British bungalows (5).

A five-point rating scale was used to evaluate the physical condition and circular performance of the selected colonial buildings. The transect walk was employed as a participatory research tool, involving systematic observation along predefined routes within Galle Fort. This method enabled the documentation of environmental, social, and infrastructural conditions while supporting a broader understanding of adaptive reuse patterns across the study area. The spatial distribution of colonial building types within Galle Fort was mapped based on their original functions and current adaptive reuse patterns. Distinct colour codes were used to represent each typology: Dutch townhouses (blue), row houses (orange), courtyard houses (green), shop houses (yellow), and service quarters (red) (Figure 2). British bungalows were identified separately due to their relatively limited presence within the fort.

The mapping analysis reveals clear differences in adaptive reuse trends among building types. Dutch townhouses, courtyard houses, and shop houses showed the highest levels of functional transformation, with many buildings being converted into boutique hotels, villas, cafés, and restaurants. This trend reflected the spatial flexibility of these structures and their suitability for tourism-oriented uses. Courtyard houses, in particular, demonstrated a strong association with heritage hotel functions, while shop houses were commonly adapted for restaurants and cafés located along the active commercial streets. In contrast, row houses largely retain their original residential function, indicating a lower degree of functional transformation and continued use as private dwellings. Service quarters exhibit the highest level of functional continuity, with many buildings still serving service-related purposes. However, notable exceptions exist, such as the former Dutch Hospital complex, which has been successfully transformed into a major hospitality and commercial centre. Overall, the spatial analysis highlights typology-specific patterns of adaptive reuse in Galle Fort, demonstrating how original building functions and spatial configurations influence contemporary reuse outcomes.

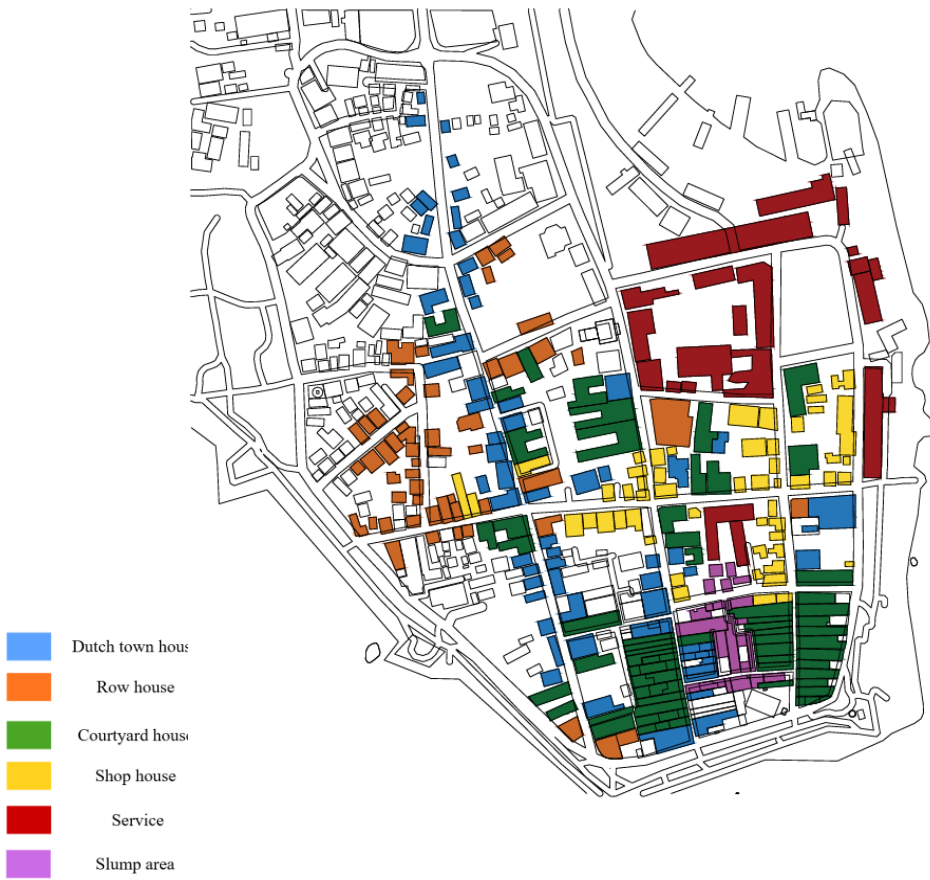
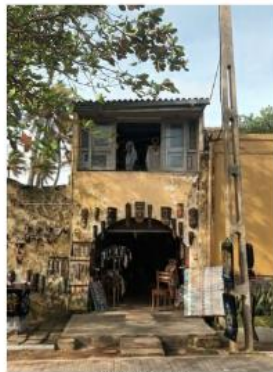


Figure 2: Map of the Galle fort showcasing the locations of different colonial buildings types



Dtuch townhouse



Shop house



Service



Courtyard house



lower income house



Row house

Figure 3: Typology of the buildings used for the assessment

Stakeholder consultations were conducted with a range of participants involved in the development and management of buildings in Galle Fort. These included architects with experience in completed and ongoing projects within the fort, building contractors, property owners, building users, and representatives from local government authorities such as the Urban Development Authority (UDA). The discussions were guided by a structured interview guide, and evaluation scores were assigned with the active participation of the stakeholders. The assessment of buildings was therefore carried out through a multi-stakeholder evaluation process, allowing the study to incorporate diverse professional, managerial, and user perspectives. For each assessment criterion, scores were determined based on the highest level of consensus reached among the participating stakeholders. Table 2 presents the composition of the study sample and the building types considered in the analysis.

Table 2: Sample profile, building types and original functions and current adaptive reuse

Colonial House Type	Original Function	Current Adaptive Reuse
Dutch Town house	Elite residence	Boutique hotels, villas
Row House	Middle-class dwelling	Cafes, guesthouses
Courtyard House	Patrician residence	Heritage hotels
Shop House	Trade residence	Restaurants, cafes
Service Quarters	Staff housing	Ancillary hospitality
British Bungalow	Administrative residence	Institutional / hotel

Source: field survey, 2025

Circular Economy Life-Cycle Assessment Framework

The assessment framework adopts a life-cycle perspective to evaluate circular economy performance across five key stages: design, manufacture and supply, construction, in-use and refurbishment, and end-of-life. At the design stage, particular attention was given to principles such as design for disassembly, adaptability, standardisation, waste reduction, and modularity. These aspects were assessed through the analysis of spatial configuration, structural logic, and the reversibility of architectural interventions. The manufacture and supply stage focuses on material-related considerations, including material optimisation, the use of durable and low-hazard materials, expected lifespan, disassembly potential, and standardisation. These factors were examined in relation to construction techniques and the accessibility of building components. During the construction stage, circularity was evaluated based on practices that minimise waste, promote the use of reused or recycled materials, and incorporate off-site construction methods where applicable. Particular emphasis was placed on the retention of original building fabric and the use of selective interventions, reflecting the extent to which existing structural and architectural elements are conserved rather than replaced. The in-use and refurbishment stage examines minimal maintenance requirements, ease of repair and upgrading, adaptability, flexibility, and functional transformation capacity to ensure long-term operational durability. Finally, the end-of-life stage assesses deconstruction potential, selective

demolition, component reuse, and both closed-loop and open-loop recycling, with particular attention to material recovery potential and the reversibility of building systems.

Table 3: Assessment Framework of Circular Economy Life-Cycle

Life-cycle Stage	Circular Economy Criteria	Assessment Focus
Design	Design for Disassembly (DfD) Adaptability Standardisation Waste Reduction Modularity	Spatial configuration structural logic reversibility of interventions
Manufacture and supply	Material optimisation low-hazard materials lifespan disassembly potential standardisation	Material durability construction techniques component accessibility
Construction	Waste minimisation reuse of materials recycled materials off-site construction	Degree of fabric retention (How much of the original building fabric (walls, floors, roofs, timber, tiles, structural systems, finishes) is kept and reused rather than demolished or replaced.) and selective intervention
In-Use and Refurbishment	Minimal maintenance ease of repair and upgrade adaptability flexibility	Functional transformation capacity and operational durability
End of Life	Deconstruction selective demolition component reuse closed-loop open-loop recycling	Material recovery potential and reversibility

Source: (Adams, K. T., Osmani, M., Thorpe, T., & Thornback, J. (2017)

Operationalization table (Table 04) brings the details of research methodology; research approach, method of data collection, analytical tools and the expected output.

Table 4: operationalization table

Objective	Approach	Method	Analysis	Expected Output

<p>To adapt and contextualize global circular economy frameworks into a locally appropriate framework, circular business model for the adaptive reuse of colonial heritage buildings within the World Heritage Site of Galle Fort, Sri Lanka.</p>	<p>Conceptual and contextual framework development</p>	<p>Systematic literature review of global CE frameworks; review of heritage conservation guidelines (UNESCO, local planning regulations); document analysis</p>	<p>Comparative analysis of global CE principles against local heritage, climatic, regulatory, and socio-economic conditions</p>	<p>A localized circular economy framework tailored to adaptive reuse of colonial heritage buildings in Galle Fort</p>
<p>To examine adaptive reuse practices through a circular economy lens, identifying how circular economy strategies are integrated into the reuse of colonial buildings.</p>	<p>Case-study</p>	<p>Multiple case studies of adaptively reused colonial buildings (boutique hotels, villas, cafés, restaurants); site observations; architectural analysis; secondary data review Reviews of visitors extracted from international hotel reservation sites</p>	<p>Qualitative and semi-quantitative assessment of CE strategies across building life-cycle stages (design, construction, use, end-of-life) Analysis of visitor reviews</p>	<p>Typology-based identification of circular economy strategies applied in adaptive reuse practices within Galle Fort</p>

3. Results and Discussion

Figure 4 presents a circular economy-based business model framework for the adaptive reuse of colonial buildings. The framework identifies key stakeholders involved in the reuse process, including property owners, architects, designers, suppliers and financial partners. Core activities focused on development, processing and the application of technical skills and appropriate technologies to support reuse interventions. Colonial building fabric, materials and human resources were identified as critical resources and capabilities, reinforcing the emphasis on maximising the value of existing assets rather than reliance on new construction. The value proposition integrates social, economic, and environmental dimensions by delivering cultural value, supporting local economies and reducing environmental impacts through material reuse. Cost structures were primarily associated with conservation and reconstruction activities, while revenue streams were generated through tourism-related uses. Customer relationships and delivery channels connect adaptive reuse projects to both local and international tourists, demonstrating how circular economy principles support value creation, delivery, and capture within heritage-led tourism development.

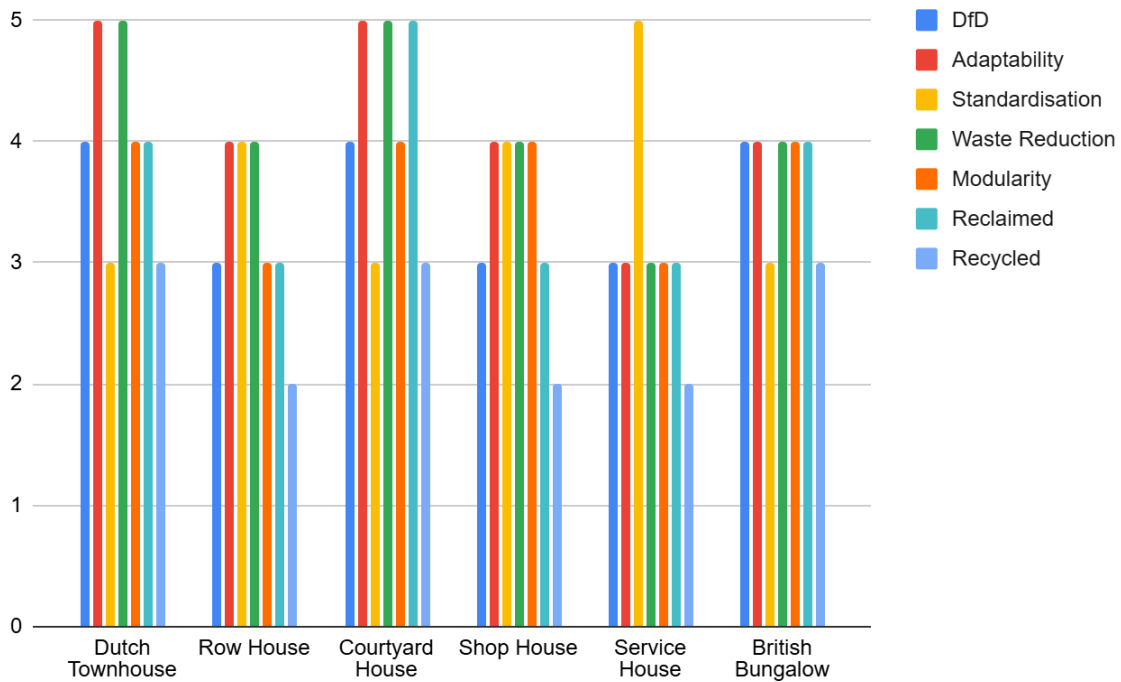


Figure 6: Life cycle stage assessment of different building types of Galle fort: Design stage

At the design stage, Dutch townhouses and courtyard houses exhibited the highest circular economy potential, particularly in adaptability and waste reduction, achieving maximum ratings. Their robust structural systems and courtyard-based spatial organisation enable reversible interventions and flexible reuse with minimal material loss, while relatively high scores for disassembly and modularity reflect ease of internal modification. Row houses and shop houses demonstrated moderate circular performance, benefiting from standardised layouts and structural regularity; however, narrow plots and shared walls limit modularity and large-scale adaptability. Service houses showed lower adaptability and modularity but high standardisation due to their simple construction systems. British bungalows present a balanced circular profile, with consistently high ratings across indicators, supported by open planning, detached form, and clear structural logic. The strong circular economy performance identified in Dutch townhouses and courtyard houses in Galle Fort aligns with observations from both global and regional adaptive reuse studies. Research on historic courtyard-based dwellings in Mediterranean cities such as Venice and Seville similarly highlights their capacity for adaptability, reversible interventions, and high levels of fabric retention, largely due to clear structural hierarchies and inward-oriented spatial organisation (Foster, 2020; Girard & Gravagnuolo, 2018).

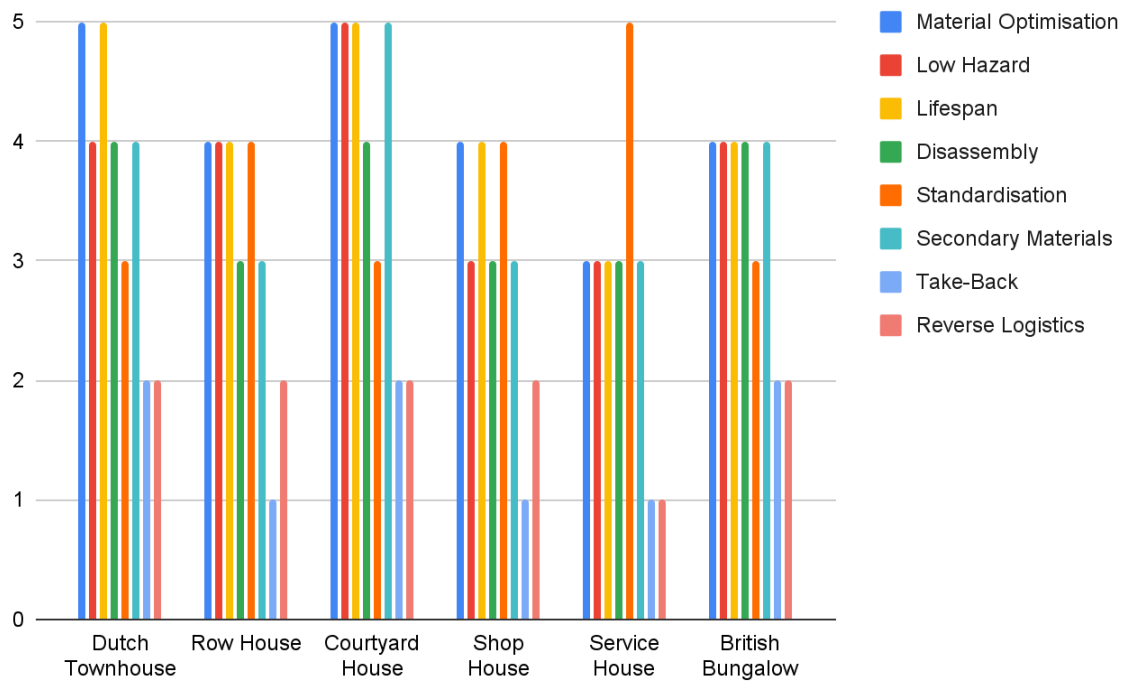


Figure 7: Life cycle stage assessment of different building types of Galle fort: Manufacture and supply

In the manufacture and supply stage (Figure 07), courtyard houses and Dutch townhouses demonstrate the highest circular performance, particularly in terms of material optimisation, lifespan, and the use of low-hazard materials. This performance was largely supported by durable traditional materials such as lime mortar, timber, and clay tiles. Moderate scores for standardisation reflect the constraints imposed by heritage conservation requirements. Row houses and shop houses exhibited moderate performance overall, with higher standardisation scores due to the repetition of construction elements within their design. Service houses perform lower in material optimisation and expected lifespan but score highly in standardisation, reflecting their relatively simple and replicable construction systems. British bungalows showed consistently strong performance, especially in disassembly potential and material longevity, facilitated by their detached form and accessible construction systems. Evidence from adaptive reuse projects in Southern Europe and the Netherlands underscores the environmental value of retaining traditional construction materials such as lime mortar, brick masonry, timber, and clay tiles (Pomponi & Moncaster, 2017). Studies of historic buildings in Italy further indicate that these materials provide long service lives, low toxicity, and high repairability, aligning closely with circular economy principles of material optimisation and low-hazard use. Comparable to Galle Fort’s colonial buildings, standardisation in these contexts remains moderate due to conservation constraints, as heritage regulations often limit the integration of modern prefabricated or standardised components (Foster, 2020).

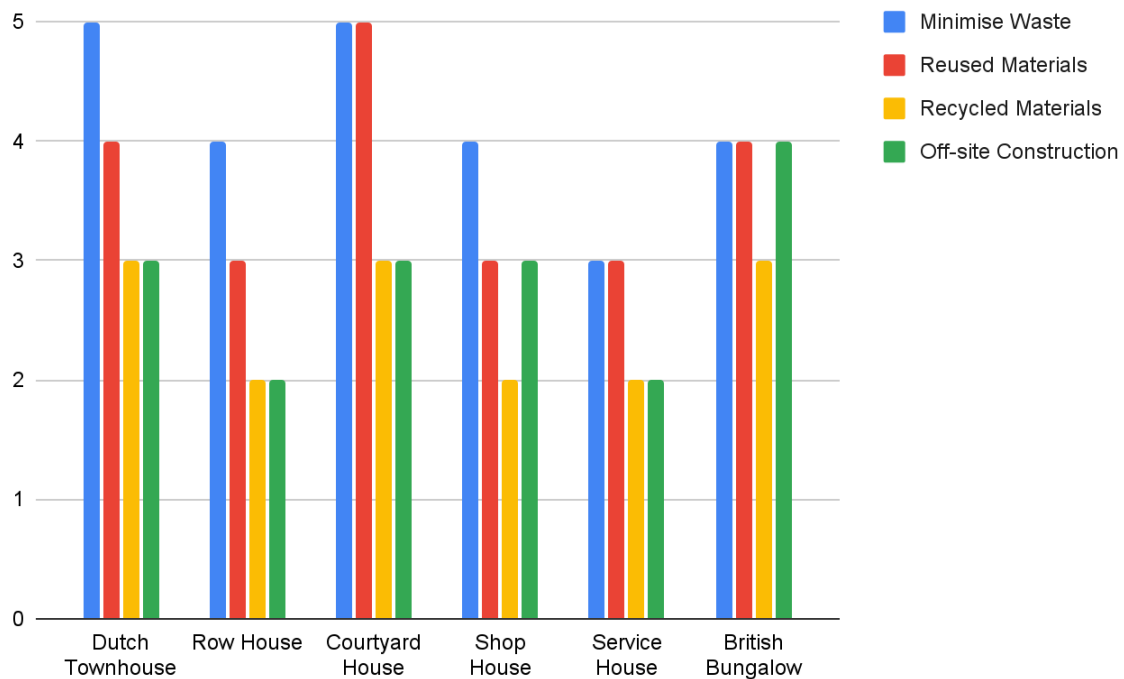


Figure 8: Life cycle stage assessment of different building types of Galle fort: construction stage

At the construction stage (Figure 8), fabric retention and selective intervention emerge as key factors influencing circular outcomes. Dutch townhouses and courtyard houses achieved the highest ratings for waste minimisation, reflecting conservation-led approaches that limit demolition, with courtyard houses also showed the greatest potential for material reuse. Row houses and shop houses demonstrated moderate performance, constrained by limited access and the smaller scale of construction, while service houses recorded lower ratings due to reduced opportunities for material recovery. British bungalows performed relatively well in terms of compatibility with off-site construction, facilitated by their detached form and the accessibility of components for prefabrication. Comparable adaptive reuse projects internationally, such as the Paddington Reservoir Gardens in Sydney and heritage regeneration initiatives in London, demonstrated strong alignment with circular economy objectives through selective demolition, fabric retention, and waste minimisation (Bullen & Love, 2011; Debacker & Manshoven, 2016). These projects emphasised conservation-led construction practices that not only reduce demolition waste but also preserve embodied carbon, highlighting the environmental value of careful intervention during the construction phase.

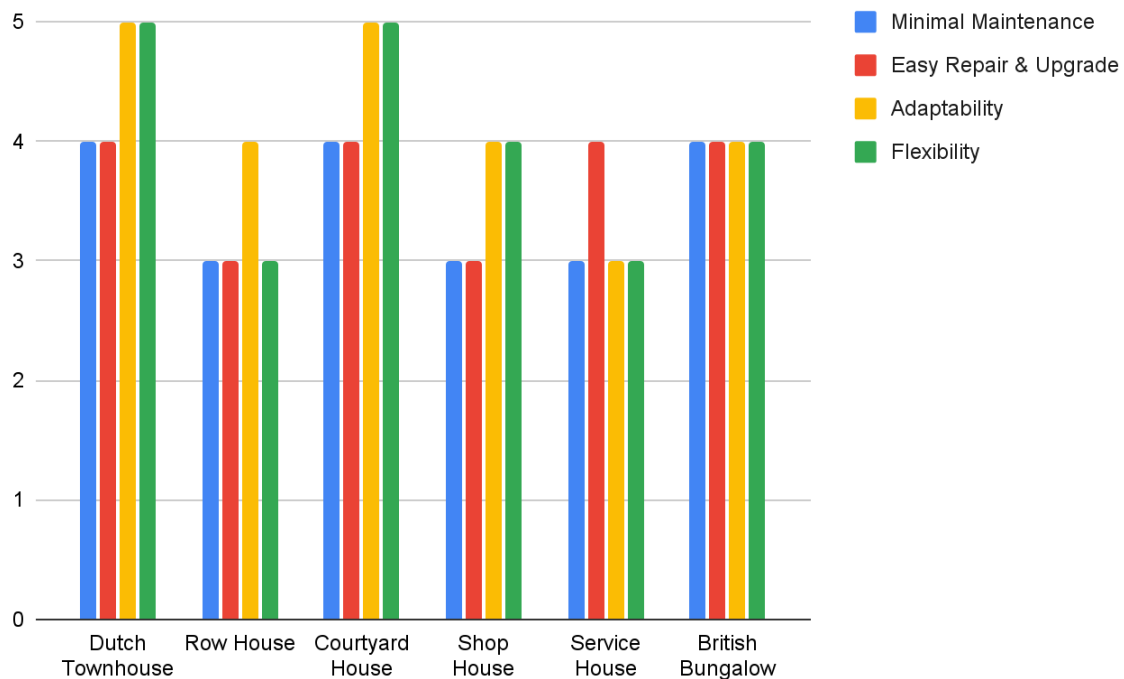


Figure 9: Life cycle stage assessment of different building types of Galle fort: In-use and refurbishment stage

In the in-use and refurbishment stage (Figure 9), Dutch townhouses and courtyard houses exhibited the highest circular performance, particularly due to their adaptability and flexibility. These features allow functional changes to occur with minimal structural intervention, while passive climatic design reduces maintenance requirements. British bungalows also performed strongly at this stage, benefiting from a balance of adaptability and ease of repair. Row houses and shop houses demonstrated moderate performance, constrained by limited spatial flexibility and intensive commercial use, whereas service houses show limited adaptability, restricting their long-term circular potential. International case studies consistently highlighted that adaptively reused heritage buildings excel in adaptability, flexibility, and extended service life (Conejos et al., 2016; Nocca, 2017). Heritage hotels and mixed-use buildings in Europe and Asia demonstrated that passive climatic design elements, such as courtyards, verandahs, and thick masonry walls, contribute to reduced maintenance requirements and lower operational energy demand. These observations closely parallel the performance of colonial courtyard houses and Dutch townhouses in Galle Fort, where buildings accommodated tourism-oriented functions with minimal structural modifications, effectively supporting circular economy objectives.

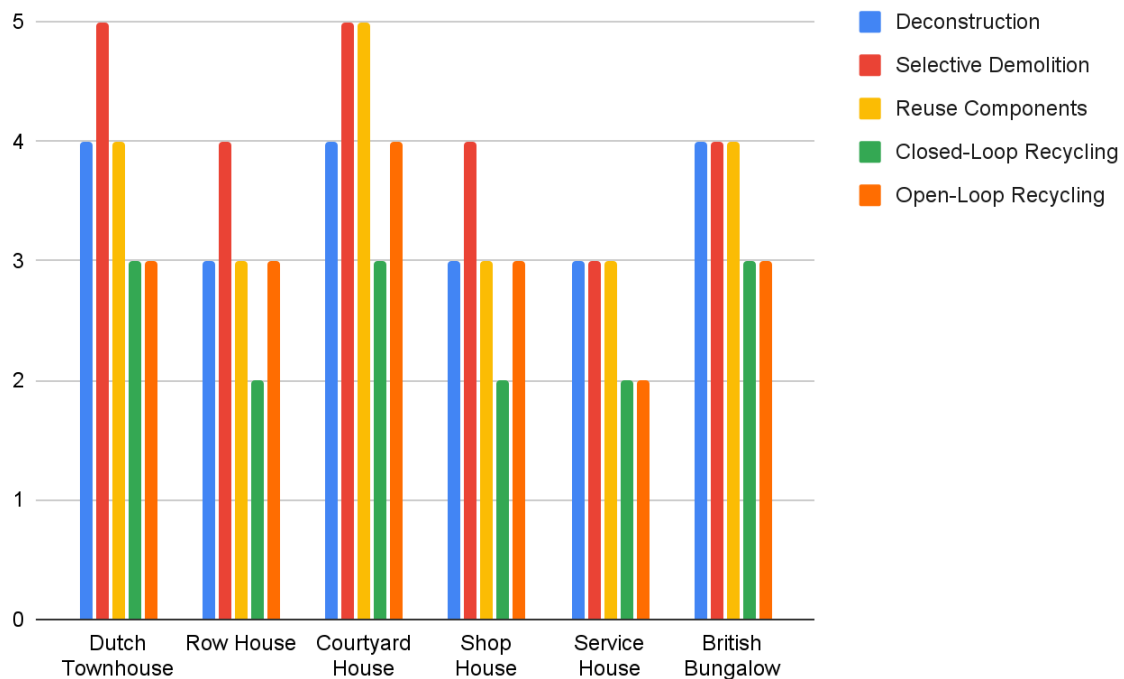


Figure 10: Life cycle stage assessment of different building types of Galle fort: End-of-life stage

At the end-of-life stage (Figure 10), courtyard houses demonstrated the highest circular potential, particularly through selective demolition and component reuse, supported by their clear structural logic and the use of durable materials. Dutch townhouses also performed strongly, enabling effective deconstruction and material recovery. Row houses and shop houses exhibited moderate recovery potential, constrained by interconnected structures and cumulative alterations over time, while service houses show the lowest circular performance due to limited opportunities for material recovery. British bungalows maintain moderate-to-high circular performance, facilitated by their detached form and the clarity of their construction materials. Research on heritage adaptive reuse in the Netherlands and Hong Kong underscores the importance of deconstruction and selective demolition as key circular strategies, which preserve material value and minimise construction waste (Foster, 2020; Osmani et al., 2008). These findings highlighted the potential for heritage buildings to contribute meaningfully to circular economy objectives, even at the end-of-life stage, when interventions were carefully planned and materials were recovered for reuse.

Detached or structurally legible heritage buildings, such as colonial bungalows and courtyard houses, enable higher levels of component reuse and material recovery compared to densely connected row buildings. Similar constraints were evident in Galle Fort, where party-wall conditions limit deconstruction potential, reinforcing the relevance of early design and use-stage circular interventions over end-of-life recovery.

4. Conclusion

Galle fort, only living world heritage site claimed for centuries old Portuguese, Dutch and British architectural masterpieces. Most of the heritage buildings are still in use and being used for socially, economically important ventures. Adaptive reuse of colonial buildings of Galle fort fosters a circular economy by repurposing structures to extend their lifespan, significantly reducing cost of new construction, reuse resources, construction waste and lowering embodied energy. Results highlighted that heritage buildings of Galle fort often have climate smart tropical architectural designs along with energy-efficient passive designs. Six main building types, Dutch townhouses, row houses, courtyard

houses, shop houses, service quarters and British bungalows were identified and strategies of circular business models include converting former residential and commercial buildings into tourism focused businesses; hotels, restaurants, villas, cafes, shop houses, etc., enhances the sustainable urban regeneration. The life-cycle-based assessment reveals clear typology-specific patterns of circular performance. Dutch townhouses and courtyard houses consistently demonstrate the highest circular economy potential across all life-cycle stages due to their robust structural systems, adaptable spatial configurations, and use of durable traditional materials. These characteristics support high levels of fabric retention, reversible interventions, and functional flexibility, particularly in tourism-oriented adaptive reuse projects. British bungalows demonstrate a balanced circular performance, benefiting from their detached forms, clear structural logic, and relative ease of disassembly and refurbishment. In contrast, row houses and shop houses show moderate circular potential, limited by narrow plots, shared walls, and intensive commercial use. Service quarters exhibit the lowest adaptability, despite maintaining strong continuity of their original functions. The study further indicates that circular economy strategies are most effectively realised during the design, construction, and in-use stages, where conservation-led decision-making, selective interventions, and passive climatic design can significantly reduce material loss and operational impacts. Circular potential at the end-of-life stage is comparatively limited, highlighting the critical importance of early-stage interventions in heritage contexts, where demolition is both undesirable and often prohibited.

References

- Amarathunga, D. (2011). Conservation practices and challenges within historic urban environments: The case of Galle Fort, Sri Lanka. *Built-Environment Sri Lanka*, 8(1), 1–12.
- Bullen, P. A., & Love, P. E. D. (2011). Adaptive reuse of heritage buildings. *Structural Survey*, 29(5), 411–421.
- CLIC Project. (2019). Circular models leveraging investments in cultural heritage adaptive reuse. Horizon 2020 Programme, European Union.
- Conejos, S., Langston, C., Chan, E. H. W., & Chew, M. Y. L. (2016). Governance of heritage buildings: Australian regulatory barriers to adaptive reuse.
- Debacker, W., & Manshoven, S. (2016). Circular economy and the built environment.
- Foster, G. (2020). Circular economy strategies for adaptive reuse of cultural heritage buildings to reduce environmental impacts.
- Girard, L. F., & Gravagnuolo, A. (2018). Circular economy and cultural heritage/landscape regeneration. *Sustainability*.
- Indika, T. N. (2020). Urban development pressures and conservation challenges in Galle Fort World Heritage Site, Sri Lanka.
- Karun, M. A., Omar, S., Ismail, W., Hussain, A. Z., & Kam, K. (2017). Adaptive reuse of heritage buildings: Assessment of sustainability performance.
- Nocca, F. (2017). The role of cultural heritage in sustainable development: Multidimensional indicators as decision-making too.
- Osmani, M., Glass, J., & Price, A. D. F. (2008). Architects' perspectives on construction waste reduction by design.
- Owojori, O., & Kim, S. (2018). Adaptive reuse as a strategy for sustainable urban development.
- Pomponi, F., & Moncaster, A. (2017). Circular economy for the built environment: A research framework.



ICRES26_029

**CONSUMER PREFERENCE DYNAMICS AND MARKET GROWTH
POTENTIAL OF REGIONALLY BRANDED AGRICULTURAL PRODUCTS IN
SRI LANKA: IMPLICATIONS FOR SUSTAINABLE REGIONAL
DEVELOPMENT**

G.P. Maddumage^{1*}, N.W.V.U. Shashikala², S.J.I.S. Wickramasinghe³

¹ *Aquinas Collage of Higher Studies, Sri Lanka.*

² *Division of Agri Business Development, Gannoruwa, Sri Lanka.*

³ *A Baur & Co (Pvt) Ltd, Sri Lanka*

**Correspondence E-mail: geethika2013@gmail.com, TP: +94712204062*

Abstract: Regional branding of Agricultural or food products is constitutes a strategic approach in promoting local produce, enhancing the market competitiveness and fostering the sustainable rural development in Sri Lanka. Despite the strategic value, the understanding of consumer preferences regarding regional agricultural brands remain insufficiently examined. The study seeks to identify the key factors influencing consumer preferences for regional agricultural brands, examine the relationship between consumer demographics and their preference for regional agricultural products, and assess consumers' willingness to pay a premium for sustainable regional agricultural products. Furthermore, the research aims to identify the market potential and barriers for the expansion of regional agricultural brands. Data were gathered from 217 respondents through face to face interviews by using semi structured questionnaire. Analyses were done by quantitative and qualitative methods. The regression results highlight the significant importance of consumer awareness, perceived quality, availability, trust through certification, belief in superiority of regional brands, emotional engagement and socio economic factors in shaping the consumer preference for regional brands. The willingness to support the local farmers, and marketing strategies centered on story telling play a vital role as powerful emotional drivers, while price remains as a limiting factor. These findings align with global research and suggest that effective branding strategies for Sri Lanka's regional agricultural products should combine awareness, authenticity, availability and emotional storytelling, alongside policy support to improve accessibility and pricing structures.

Keywords; Regional agricultural brand; Consumer preference; Market growth potential; Sustainability

1. Introduction

As global markets grow continually competitive and consumer preferences become more sophisticated, the development of strong regional agricultural brands has emerged as a vital strategy for enhancing rural livelihoods and improving national economic growth (Ilbery & Kneafsey, 2000; Belletti et al., 2017). In Sri Lanka, where agriculture is a key sector supporting rural communities and contributing significantly to employment and food security, branding regional agricultural products offers an opportunity to capture added value, differentiate local produce, and expand market reach both domestically and internationally. Other than that, previous studies highlights that consumers tend to associate regionally produced agricultural products with sustainability due to different factors. The shorter supply chains, reduced transportation related environmental impacts, and stronger support for local agricultural economies, highlighting the potential of regional brands to contribute to environmentally and socio economically sustainable food systems (Feldmann & Hamm, 2015). However, the potential of such branding initiatives depends fundamentally on understanding consumer preferences and aligning product offerings with market expectations (van Ittersum et al., 2007).

In addition to Sri Lanka's rich diversity of agricultural commodities including globally recognized products such as Ceylon tea, spices, indigenous rice varieties, and tropical fruits, many regional products remain underdeveloped in terms of brand identity and market positioning (Athukorala & Jayasuriya, 2012). Agricultural products such as "Ruhunu Meekiri, Bibile orange, Nawala pineapple, are famous among local people, but there is no global identity or proper branding for them. Challenges such as inconsistent quality standards, fragmented supply chains, and limited market research have constrained the success of regional brands (Wickramasinghe & Cameron, 2002). As well, a global rise in consumer awareness about product origin, authenticity, and sustainability is creating new opportunities for agricultural products that reflect the unique characteristics of Sri Lanka's diverse agro ecological zones (Tregear, 2003; Barjolle & Sylvander, 2000).

It is very important to identify the key factors that drive consumer preferences including quality, price, origin labeling, certification, and brand reputation is critical for crafting effective branding and marketing strategies (Verbeke & Ward, 2006). Other than that, assessing consumers' willingness to pay a premium and their purchasing behavior provides valuable insights into the market potential for developing and expanding regional agricultural brands (Grunert, 2005). However, empirical research that systematically explores these aspects in the Sri Lankan context remains limited, creating a critical knowledge gap.

The purpose of this study is to address this gap by systematically analyzing consumer preferences and evaluating the market potential of regional agricultural brands in Sri Lanka. By examining the determinants that influence consumer choices and estimating willingness to pay for branded regional products, the research seeks to provide actionable insights for policymakers, producers, and marketers to enhance the competitiveness and sustainability of Sri Lanka's agricultural sector.

2. Materials and Methods

This study was conducted using the mixed method approach, integrating both quantitative and qualitative data collection to comprehensively understand consumer preferences for regional agricultural brands in Sri Lanka.

2.1 Data Collection

Primary data were collected through face to face interviews using a semi structured questionnaire, designed to collect the data on consumer demographics, awareness, perceived quality, availability, trust through certification, belief in superiority of regional brands, emotional engagement, and willingness to pay a premium for regional agricultural products. In addition to that using additional sections of the questionnaire collected data on market barriers and potential expansion strategies for regional brands, consistent with best practices in consumer preference studies (Sirieix et al., 2008; Fernqvist & Ekelund, 2014). To ensure the clarity and suitability of the questionnaire, it was pre tested with a small sample (n = 20). The pre test was conducted to identify ambiguities, unclear wording, and potential issues in

the structure of the questions. Based on the feedback received, several revisions were made to improve the clarity and relevance of the items.

In addition, the reliability of the multi item scales used in the questionnaire was assessed using Cronbach’s alpha to evaluate the internal consistency of the constructs

A non probability sampling technique was employed, targeting Sri Lankan consumers across different demographic groups (including urban and rural areas) to enhance the representativeness. A minimum of 217 respondents was targeted for sufficient statistical power,

2.2 Data Analysis:

Collected data were analyzed using descriptive statistics to identify general trends and patterns in consumer preferences. The binary logistic regression model was used to assess the impact of key factors including consumer awareness, perceived quality, availability, trust through certification, belief in superiority of regional brands, emotional engagement, and socio-economic factors on the likelihood of consumers preferring regional brands.

The regression model was specified as:

$$\begin{aligned} \text{Logit}(P(Y=1)) = & \beta_0 + \beta_1 (\text{Awareness}) + \beta_2 (\text{Perceived Quality}) + \beta_3 (\text{Availability}) \\ & + \beta_4 (\text{Trust}) + \beta_5 (\text{Belief in Superiority}) + \beta_6 (\text{Emotional Engagement}) \\ & + \beta_7 (\text{Premium Price}) + \beta_8 (\text{Packaging}) + \beta_9 (\text{Value addition}) \\ & + \beta_{10} (\text{Income}) + \beta_{11} (\text{Age}) + \beta_{12} (\text{Gender}) + \varepsilon \end{aligned}$$

where Y is a binary dependent variable indicating special preference for Regional Agricultural Brands (1 = prefer, 0 = do not prefer).

Data cleaning, descriptive analyses, and preliminary cross tabulations were done using Microsoft Excel, and binary logistic regression analyses were conducted using the Statistical Package for Social Sciences (SPSS) software (version 26.0).

To ensure the robustness of the logistic regression model, goodness-of-fit tests (specifically the Hosmer-Lemeshow test) and the Omnibus Tests of Model Coefficients were conducted. These diagnostic measures verified the reliability of the coefficient estimates, aligning with the recommendations of Hair et al. (2010) and consistent with similar studies in market and consumer behavior research. Participation in the study was voluntary and based on informed consent. Confidentiality and anonymity of respondents were strictly maintained throughout the data collection and analysis phases, to fulfil ethical standards for social science research.

3. Results and Discussion

This section presents the descriptive and statistical analysis results of the study, providing an integrated interpretation of the factors influencing consumer preferences for regional agricultural brands in Sri Lanka.

3.1 Descriptive Statistics of Key Predictors

Table 3.1 summarizes the frequency distributions and proportions of key predictor variables, giving a foundational understanding of respondents’ perceptions and preferences.

Table 3.1: Descriptive Statistics of Key Predictors (n = 217)

<i>Variable</i>	<i>Categories</i>	<i>Frequency</i>	<i>Percentage (%)</i>
<i>Awareness</i>	Not aware (0)	58	26.7
	Aware (1)	159	73.3
<i>Quality</i>	Low (1–2)	27	12.4
	Moderate (3)	25	11.5
	High (4–5)	165	76.0
<i>Availability</i>	Low (1–2)	66	30.4

	Moderate (3)	70	32.3
	High (4–5)	81	37.3
<i>Trust through certification</i>	Low (1–2)	17	7.8
	Moderate (3)	65	30.0
	High (4–5)	135	62.2
<i>Belief in superiority</i>	Not Believe (0)	78	35.9
	Believe (1)	139	64.1
<i>Intention to Support for Local Farmers (Emotional Engagement)</i>	Low (1–2)	74	34.1
	Moderate (3)	30	13.8
	High (4–5)	113	52.1
<i>Willingness to pay premium Price</i>	Low (1–2)	46	21.2
	Moderate (3)	144	66.4
	High (4–5)	27	12.4
<i>Significance of Packaging</i>	Low (1–2)	90	41.5
	Moderate (3)	67	30.9
	High (4–5)	60	27.6
<i>Expectation of Value Addition</i>	Low (1–2)	62	28.7
	Moderate (3)	118	54.6
	High (4–5)	36	16.7

According to the descriptive analysis it reveals that robust levels of awareness (73.3%) and perceived quality (76.0% high ratings), suggesting that these factors are widely recognized among consumers. As well emotional engagement factors also appear strong, with 62.2% of respondents assigning high importance to trust through certification and 52.1% emphasizing their intention to support for local farmers. On the other hand, availability shows a more balanced distribution, with only 37.3% assigning it high importance, suggesting that practical access to regional products may be an area of concern.

According to the analysis, willingness to pay premium is moderate and high, 66.4% and 12.5% in ratings, and low (21.1%), indicating a perception of price as a potential limiting factor. However, as subsequent regression analyses reveal, this concern does not significantly impact actual preferences in this context. The value addition is strongly recognized among consumers, with 71.4% of respondents rating it at level 3 or higher, and only 11.6% giving it the lowest rating. This suggests that most consumers place moderate to high importance on value added features, highlighting its relevance in shaping preference and perceived product quality.

3.2 Regression Results and Interpretation

Binary logistic regression was employed to identify significant predictors of consumer preference for regional agricultural brands. The Hosmer and Lemeshow test confirmed that the model fit the data well ($\chi^2 = 5.864$, $df = 8$, $p = 0.663$), and the Omnibus Tests of Model Coefficients were significant ($p < 0.05$), indicating the model's overall validity.

According to the regression results, awareness, quality, availability, trust through certification, Belief in Superiority, support for local farmers, income, and age were emerged as statistically significant positive predictors ($p < 0.05$) (Table 3.2). These findings suggest that consumer preference is strongly shaped by perceptual and emotional drivers, as well as by socio-economic factors.

Table 3.2: Binary Logistic Regression Results

<i>Predictor</i>	<i>B</i>	<i>S.E.</i>	<i>p-value</i>	<i>Exp(B)</i>	<i>95% CI Lower</i>	<i>95% CI Upper</i>
<i>Awareness</i>	3.435	1.021	0.001***	31.026	4.196	229.417
<i>Quality</i>	0.941	0.367	0.010**	2.563	1.248	5.263
<i>Availability</i>	0.734	0.360	0.042*	2.082	1.028	4.218
<i>Trust through certification</i>	1.160	0.452	0.010**	3.188	1.316	7.728

<i>Belief in superiority</i>	2.152	0.735	0.003**	8.606	2.039	36.320
<i>Intention to Support for Local Farmers</i>	1.826	0.424	<0.001***	6.208	2.703	14.255
<i>Income</i>	0.000	0.000	0.019*	1.000	1.000	1.001
<i>Age</i>	0.065	0.032	0.042*	1.068	1.003	1.137
<i>Willingness to pay premium price</i>	-0.211	0.301	0.482	0.810	0.449	1.460
<i>Significance of Packaging</i>	0.171	0.245	0.487	1.187	0.734	1.920
<i>Expectation of Value Addition</i>	0.896	1.255	0.475	2.449	0.209	28.654
<i>Gender</i>	0.603	0.661	0.362	1.827	0.500	6.681
<i>Constant</i>	-24.553	5.583	<0.001***	0.000	-	-

These findings strongly support the statistical importance of awareness ($p = 0.001$), perceived quality ($p = 0.010$), availability ($p = 0.042$), trust through certification ($p = 0.010$), and emotional engagement, measured by Support for local farmers ($p < 0.001$), in shaping consumer preferences for regional agricultural brands. The notably high odds ratio for awareness (Exp B = 31.026) underscores that consumer knowledge is a powerful gateway to preference adoption. This finding is also consistent with prior research on information dissemination and consumer engagement (Fernqvist & Ekelund, 2014).

The statistically significant influence of perceived quality (Exp B = 2.563) and availability (Exp B = 2.082) affirms the critical role of tangible product attributes in driving loyalty. In the same way, trust through certification (Exp B = 3.188) and belief in brand superiority (Exp B) = 8.606) significantly impact preference, highlighting the importance of strategic branding and communication. Emotional drivers such as support for local farmers (Exp B) = 6.208) further demonstrate how ethical alignment and local identity strengthen consumer relationships.

In spite of not being statistically significant in the regression model ($B = -0.211$, $p = 0.482$), willingness to pay a premium price emerges as a notable perceptual concern among consumers. Descriptive analysis reveals that 66.4% of respondents rated their willingness to pay as moderate, and 12.4% are high, while 21.1% indicated low willingness, suggesting a cautious attitude toward price premiums. This highlights that although price is perceived as a limiting factor, it does not exert a significant behavioral influence when compared to stronger emotional and perceptual drivers such as awareness, quality, and emotional connection. Therefore, while price sensitivity should not be ignored, it appears to be outweighed by other motivating factors in consumer decision-making for regional agricultural brands. Finally, income ($p = 0.019$) and age ($p = 0.042$) emerged as significant positive predictors, suggesting that older and higher-income consumers are more receptive to the authenticity, cultural value, and identity embedded in regional brands.

4. Conclusion

This study provides a deeper understanding of the factors that influence consumers' preferences for regional agricultural brands in Sri Lanka, an area that has received relatively little attention despite its increasing importance for rural development and strengthening local market competitiveness. The findings reveal that consumer preferences are influenced by a combination of perceptual, emotional, and socio-economic factors. In particular, awareness of regional brands, perceptions of product quality, product availability, trust built through certification, the belief that regional brands are superior, and the desire to support local farmers all play important roles in shaping consumer choices.

Although many respondents considered price to be a potential barrier, the results showed that it did not have a statistically significant effect on actual consumer preferences. This suggests that stronger perceptual and emotional factors such as trust in the brand and a sense of cultural connection play a more influential role in shaping consumer decisions. In addition, the significant effects of income and age highlight that demographic characteristics also influence how consumers perceive and accept regional brands. These insights align with global literature and underscore the need for strategic

branding approaches that incorporate authenticity, accessibility, emotional storytelling, and policy level support. Enhancing brand visibility, building consumer trust, and improving distribution networks can further elevate the market potential of Sri Lankan regional agricultural products.

The findings of this study provide several practical insights for promoting and expanding regional agricultural brands in Sri Lanka. One of the most important priorities is increasing consumer awareness. Marketing efforts should focus on communicating the origin, uniqueness, and cultural value of regional products so that consumers better understand what makes them special. Campaigns that use emotional storytelling and highlight local identity, tradition, and ethical consumption can help create a stronger connection between consumers and these products.

Another key area is building consumer trust. Certification systems and clear quality assurance mechanisms can play an important role in strengthening credibility. When consumers feel confident that a product is authentic and meets reliable quality standards, they are more likely to choose regional brands. At the same time, improving product availability is equally important. Expanding distribution networks especially in areas where such products are currently difficult to find will help ensure that consumers who prefer regional brands are actually able to purchase them.

From a policy perspective, supportive measures are also necessary. Improving distribution infrastructure can help make regional products more widely accessible. In addition, financial support mechanisms, such as incentives for regional brand producers, could help reduce production costs and address concerns related to price sensitivity. Together, these efforts can enhance the visibility, accessibility, and competitiveness of regional agricultural brands while contributing to broader rural development objectives in Sri Lanka.

Overall, by combining empirical findings with practical interpretation, this study offers useful guidance for policymakers, marketers, and producers who aim to strengthen the presence and impact of regional agricultural brands in Sri Lanka and other similar emerging markets.

References

- Athukorala, P. and Jayasuriya, S., 2012. Food security in Sri Lanka. *Asia Pacific Development Journal*.
- Barjolle, D. and Sylvander, B., 2000. Some factors of success for origin labelled products in agri-food supply chains in Europe: market, internal resources and institutions. *Acta Agriculturae Scandinavica*.
- Belletti, G., Marescotti, A. and Touzard, J.M., 2017. Geographical Indications, public goods, and sustainable development: The roles of actors' strategies and public policies. *World Development*, 98, pp.45–57.
- Department of Census and Statistics Sri Lanka, 2022. Sri Lanka labour force statistics: Annual report. [online] Available at: <<https://www.statistics.gov.lk>> [Accessed Day Month Year].
- Fernqvist, F. and Ekelund, L., 2014. Credence and the effect on consumer liking of food: A review. *Food Quality and Preference*, 32, pp.340–353.
- Grunert, K.G., 2005. Food quality and safety: consumer perception and demand. *European Review of Agricultural Economics*, 32(3), pp.369–391.
- Hair, J.F., Black, W.C., Babin, B.J. and Anderson, R.E., 2010. *Multivariate data analysis*. 7th ed. Upper Saddle River, NJ: Prentice Hall.
- Ilbery, B. and Kneafsey, M., 2000. Producer constructions of quality in regional speciality food production: A case study from South West England. *Journal of Rural Studies*, 16(2), pp.217–230.
- Sirieix, L., Delanchy, M., Remaud, H., Zepeda, L. and Gurviez, P., 2008. Consumers' perceptions of food products: The case of regional and organic products. *Food Quality and Preference*, 19(6), pp.434–445.
- Tregear, A., 2003. From Stilton to Vimto: Using food history to re-think typical products in rural development. *Sociologia Ruralis*, 43(2), pp.91–107.
- van Ittersum, K., Meulenbergh, M.T.G., van Trijp, H.C.M. and Candel, M.J.J.M., 2007. Consumers' appreciation of regional certification labels: A pan-European study. *Journal of Agricultural Economics*, 58(1), pp.1–23.
- Verbeke, W. and Ward, R.W., 2006. Consumer interest in information cues denoting quality, traceability and origin: An application of ordered probit models to beef labels. *Food Quality and Preference*, 17(6), pp.453–467.
- Wickramasinghe, U. and Cameron, D., 2002. Sri Lanka's agricultural policy and strategy: The need for a new approach. *Sri Lanka Economic Journal*.

ICRES26_030

**INVESTIGATION OF INCORPORATION OF RECYCLED ASPHALT
AGGREGATES IN RIGID PAVEMENTS IN SRI LANKA****U.L.M. Akeel*, H.W.K. Sandeep, G.G.T. Madhushan, A.A.S.U. Gunarathna***University of Vocational Technology, Rathmalana.***Correspondence E-mail: ulmakeel5@gmail.com, TP: +94776476940*

Abstract: The construction industry is increasingly focusing on sustainable practices in order to reduce environmental impacts and conserve natural resources. One possible approach is the reuse of construction waste materials in new infrastructure projects. Reclaimed Asphalt Pavement (RAP), which is produced during road rehabilitation and maintenance activities, contains valuable aggregates that can potentially be reused in concrete. This study investigates the feasibility of using Recycled Asphalt Aggregates (RAA) obtained from RAP as a partial replacement for natural coarse aggregates in rigid pavement concrete in Sri Lanka. RAP materials were collected and processed through heating, crushing, sieving, and washing to obtain suitable RAA particles. The physical and mechanical properties of RAA were tested and compared with those of conventional aggregates. Concrete specimens were prepared by replacing natural coarse aggregates with RAA at replacement levels of 0%, 5%, 10%, 15%, and 20%. The performance of the concrete mixtures was evaluated through slump tests, compressive strength tests, and flexural strength tests. In addition, Scanning Electron Microscopy (SEM) analysis was conducted to examine the microstructural characteristics of the concrete. The results showed that RAA has slightly lower specific gravity and higher water absorption compared to natural aggregates. Although increasing RAA content reduced the compressive strength of concrete, the mix containing 5% RAA still achieved a compressive strength of 27.87 N/mm² after 28 days, which satisfies the requirements for Grade 25 concrete used in rigid pavements. Flexural strength also remained within acceptable limits. The findings indicate that a small percentage of RAA can be successfully used in rigid pavement concrete without significantly affecting performance. Therefore, the use of RAA offers a sustainable solution for reducing asphalt waste and conserving natural aggregate resources in Sri Lanka.

Keywords: Recycled Asphalt Aggregate (RAA); Rigid Pavement; Aggregate; Concrete

1. Introduction

The concrete production requires a large amount of natural or virgin aggregates, which causes both environmental and economic problems (Mostafa, et al., 2017). Using recycled materials such as Recycled Asphalt Aggregates (RAA), obtained from old asphalt pavement waste, can reduce this impact, extract the valuable materials from waste and support sustainability in the construction sector (Kavitha , et al., 2023). And also, the country faces challenges in managing construction waste and maintaining sustainability in material use. Incorporating RAA into rigid pavement construction could help address these challenges by reducing the need for new raw materials while promoting eco-friendly practices (Jaime, et al., 2024).

Recycled Asphalt Aggregates (RAA) are produced by crushing and processing reclaimed asphalt pavement (RAP) (Kavitha , et al., 2023). This material contains aged asphalt binder and aggregates, which can be reused in new construction. Many countries have successfully used RAA in flexible pavements, but its use in rigid concrete pavements is still being explored. One of the main concerns when using recycled asphalt aggregates in concrete is the presence of the asphalt coating on the aggregate surface. This coating may affect the bond that forms between the aggregate particles and the surrounding cement paste, which can influence the strength and long-term durability of the concrete. Despite this concern, the use of RAA in rigid pavement construction provides several advantages. Reusing these materials can help reduce construction costs, decrease environmental impacts associated with natural aggregate extraction, and support sustainable construction practices by promoting the reuse of waste materials within a circular economy framework. (Jaime, et al., 2024).

Before recycled asphalt aggregates can be widely used in Sri Lanka, it is important to carefully examine their characteristics and performance under local environmental and construction conditions. Evaluating the physical and mechanical behaviour of RAA, and comparing it with conventional natural aggregates, is necessary to ensure that rigid pavements maintain the required strength and durability. Although many international studies have investigated the use of recycled asphalt materials in pavement construction, research related to their application in Sri Lanka remains limited. Therefore, this study focuses on assessing the suitability of Recycled Asphalt Aggregates for rigid pavement concrete in the Sri Lankan context and aims to contribute knowledge that can support more sustainable construction practices in the future.

Recycled asphalt aggregates possess certain characteristics that may improve the performance of rigid pavement concrete, particularly in terms of strength and long-term durability. (Salim, et al., 2009). This study aims to assess the performance of recycled asphalt aggregates when used in rigid pavement concrete under the climatic and traffic conditions found in Sri Lanka. The results of this research are expected to provide useful knowledge for enhancing pavement quality and service life. In the long term, these findings may contribute to developing safer, more durable, and economically efficient road infrastructure within the country.

2. Objectives

To investigate the physical and mechanical properties of recycled asphalt aggregates in rigid pavements.
To determine the optimum mix ratio of concrete with coarse aggregate partially replaced by Recycled Asphalt Aggregate (RAA) for rigid pavement.

3. Methodology

The study uses an experimental research design to investigate the physical, mechanical, and performance characteristics of Recycled Asphalt Aggregates (RAA) when incorporated into rigid pavement concrete. This research is involving a series of laboratory tests to determine the effectiveness of replacing a portion of the natural coarse aggregates with RAA in concrete mixtures. The figure 1. Shows the experimental methodology used in this study.

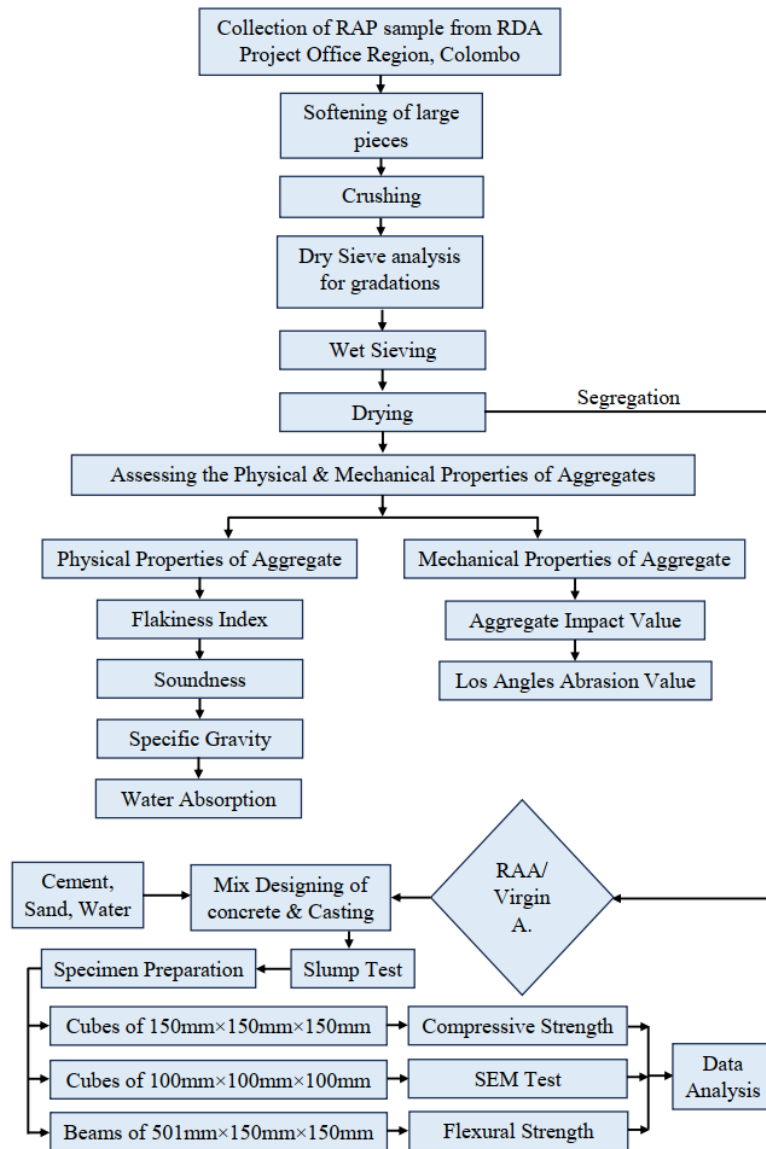


Figure 1: Flow Chart of Methodology

3.1. Preparation of RAA

The RAP was included 15 years old asphalt pavements removed during road milled at Homagama – Pitipana RDA Road (A004). Then collected RAP materials were softened in an oven at a temperature of 150°C for about 45 minutes to crushing easier. After heating, the softened RAP materials were gently crushed using a steel rod and timber rod by hand rolling to break them into smaller, manageable sizes. The coarse RAP aggregates were retained above 5mm by sieving. And also, wet sieving was carried out to remove loose dust particles. After wet sieving, the aggregates were dried naturally in the sun and Figure:2 shows the steps of RAA preparation.



Figure 2: Procedure of RAA Preparation

3.2. Characterization of RAA and Virgin Aggregates

Both RAA and virgin coarse aggregates were subjected to a series of laboratory tests to determine and compare their physical and mechanical properties to full fill the specific range of aggregates for concrete to rigid pavement. Such as, Flakiness Index, Soundness test, Specific Gravity of coarse aggregates, Water Absorption, Aggregate Impact Value and Loss Angeles Abrasion Value were conducted in accordance with ICTAD SCA/5: Section 1801.6, based on BS 812 Part 105.1, ASTM C88, ICTAD SCA/5: 1801.7, based on ASTM C127, ICTAD SCA/5 Section: 1701.3 not more than 2%, based on ASTM C127, ICTAD SCA/5: Section 1801 shall not be greater than 45, based on BS 812 Part 112, and ICTAD SCA/5: Section 1801.1, based on ASTM C131 respectively (Institute for Construction Training and Development (ICTAD), 2009).

3.3. Materials and Concrete

A concrete mix design was prepared with weight proportion as according to ICTAD SCA/5: Section 901A.3(a) to prepare Grade 25 (G25) concrete to find the materials quantities. Then, cement, fine aggregate, and water were taking with weight proportion in accordance with ICTAD SCA/5: Section 901B.2(a), ICTAD SCA/5: Section 901B.2(c), and ICTAD SCA/5: Section 901B.2(b) respectively (Institute for Construction Training and Development (ICTAD), 2009).

And also, RAA was partially replaced virgin crushed coarse aggregate with concerning gradation as according to ICTAD SCA/5: Table: 1701.1 at 5%, 10%, 15% and 20% of each size of 5mm and 10mm and table:1, shows the aggregate distribution with proper gradation in weight proportion for 03 cubes of each percentage (Institute for Construction Training and Development (ICTAD), 2009).

Table 1: Coarse Aggregate Distribution with Gradation of Each Size:

Grading for Coarse Aggregate for Concrete												
Sieve Size (mm)	Retained %	Mixed Design Amount of Coarse Aggregate (kg)	Gradation Weights of Coarse Aggregate for Mix Design (kg)	Percentage Distribution (%)	Aggregate Distribution of Virgin and RAA							
					Mix of 5%		Mix of 10%		Mix of 15%		Mix of 20%	
					Virgin Aggregate of 95% of each size	Replace of RAA - 5% of each size(kg)	Virgin Aggregate of 90% of each size	Replace of RAA - 10% of each size(kg)	Virgin Aggregate of 85% of each size	Replace of RAA - 15% of each size(kg)	Virgin Aggregate of 80% of each size	Replace of RAA - 20% of each size(kg)
10	51.5	29.882	15.389	50	14.620	15.39×05%	13.850	15.39×10%	13.081	15.39×15%	12.311	15.39×20%
				0.769		1.539				2.308		
5	42	29.882	12.550	50	11.923	12.55×05%	11.295	12.55×10%	10.668	12.55×15%	10.040	12.55×20%
				0.628		1.255				1.883		
Pan	6.5		1.942	Totally Replaced by Virgin Coarse Aggregate								
Total Aggregate		29.882	29.882	100	29.882		29.882		29.882		29.882	

Then, the cubes of 03 samples for each percentage (RAA - 0%,5%,10%,15% and 20%) of RAA and the beam specimens of 03 samples for control (RAA - 0%) and optimum mix ratio (RAA - 5% from found Compressive Strength) were cast and cured following standard procedures to make sure the results were consistent and comparable. According with ICTAD SCA/5: Section 901B (Institute for Construction Training and Development (ICTAD), 2009).

3.4. Experimental Investigation of Gr 25 Concrete for Rigid Pavement

This experimental phase evaluated the physical and mechanical performance of RAA incorporated concrete compared with control samples (0% - RAA). Under section 901B.3 (Institute for Construction Training and Development (ICTAD), 2009). Such as, Workability of Concrete, Compressive Strength of Concrete, and Flexural Strength of Concrete were conducted in accordance with ICTAD SCA/5: Section 901A.3(b), ICTAD SCA/5: Section 901A.3(b), based on ASTM C78 respectively (Institute for Construction Training and Development (ICTAD), 2009).

And also, The Scanning Electron Microscopy (SEM) test was carried out the microstructural characteristics of concrete containing RAA (Optimum RAA mix ratio from previous compressive strength - 5%) and Control (0%) to observe the morphology, the internal surface and bonding behaviour between the cement paste and aggregates at a microscopic level.

4. Results

4.1. Physical & Mechanical Properties of Conventional and RAA Aggregates

Table 2: Aggregate Properties of Virgin VS RAA

Conducted Test on Material					Standard	
No.	Test Name	Virgin	RAA	Testing Method	Limit Value	Standard Consideration
1	Flakiness (%)	20	7	BS 812; Part 105.1	<35	ICTAD - SCA05; Section 1701.2 (BS-812)
2	AIV (%)	27	13	BS 812; Part 112	<45	ICTAD - SCA05; Section 1701.2 (BS-812)
3	LAAV (%)	46	24	ASTM C131	33 - 57	ICTAD - SCA05; Section 1801.5 (ASTM C131-01)
4	Soundness (%)	3.3	2.8	ASTM C88	< 12	ICTAD - SCA05; Section 1801.9
5	Water Absorption (%)	0.489	0.72	ASTM C127	0.2 - 4	ASTM C127
6	Specific Gravity	2.671	2.613	ASTM C127	2.5 - 3	ICTAD - SCA05; Section 1801.7 ASTM C127

The aggregate properties revealed significant differences between conventional aggregates and RAA and table: 2 shows the properties of values of virgin and RAA. The flakiness index of the recycled asphalt aggregates was found to be lower than that of the conventional aggregates, with values of 7% and 20% respectively. This result indicates that RAA particles have a more favourable shape, which can contribute positively to the workability and strength development of concrete. In addition, the soundness test results for both aggregate types were relatively close, recording 3.3% for conventional aggregates and 2.8% for RAA. These values suggest that both materials have a similar resistance to weathering effects and environmental deterioration.

The measured specific gravity of recycled asphalt aggregates was 2.613, which is slightly lower than the value of 2.671 recorded for conventional aggregates. This difference is likely caused by the thin layer of aged asphalt binder that remains on the surface of the recycled particles. Because of this variation in specific gravity, it is important to consider the effect during the concrete mix design process so that the correct volume proportions of materials are maintained.

The results indicated that recycled asphalt aggregates had a higher water absorption value of 0.72%, whereas the conventional aggregates recorded 0.489%. This increase in absorption may be related to the relatively porous characteristics of the aged asphalt layer surrounding the recycled particles or the existence of small internal cracks within them. If this higher absorption is not properly considered during the mix design stage, it may influence the workability of fresh concrete and could also affect its strength.

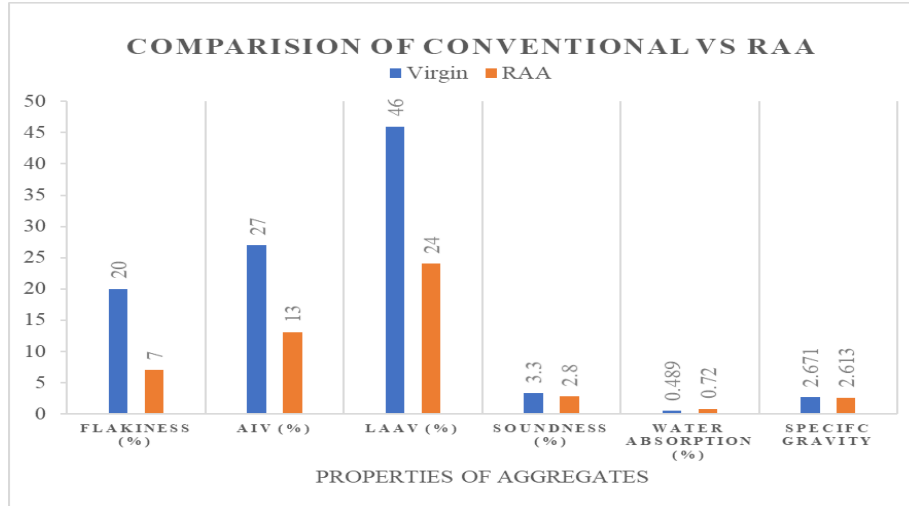


Figure 3: Aggregate Properties of Virgin VS RAA with Percentage

Regarding mechanical performance, the recycled asphalt aggregates exhibited greater resistance to both impact and abrasion when compared with conventional aggregates. The Aggregate Impact Value (AIV) for RAA was recorded as 13%, which is considerably lower than the 27% obtained for natural aggregates, indicating a stronger ability to withstand sudden impact loads. In a similar manner, the Los Angeles Abrasion Value (LAAV) of RAA was 24%, while conventional aggregates showed a much higher value of 46%. This result suggests that RAA has better resistance to surface wear and degradation. The improved mechanical behaviour of RAA is likely related to the residual asphalt layer on the particles, which may act as a cushioning and protective coating that helps dissipate impact forces.

4.2. Concrete Properties

4.2.1. Workability of Fresh Concrete

The slump test results showed that all mixes had acceptable workability for rigid pavement applications (10-30 mm slump (Institute for Construction Training and Development (ICTAD), 2009)), RAA incorporation does not adversely affect the workability of concrete.

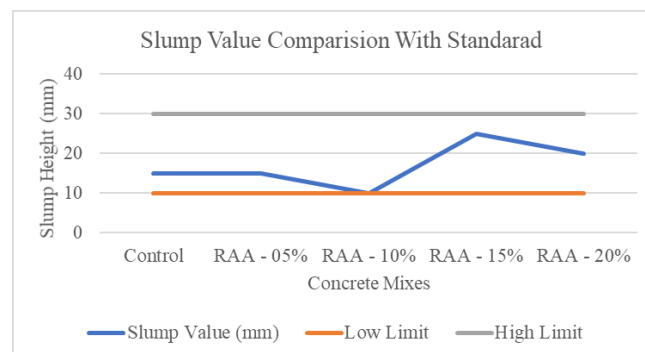


Figure 4: Slump Value Comparison with Standard values:

4.2.2. Compressive Strength

The compressive strength results clearly showed a decreasing trend with increasing RAA content. At 7 days, the strength reduction compared to the control mix was 17.6% for 5% RAA, 24.4% for 10% RAA, 40.1% for 15% RAA, and 55.8% for 20% RAA. At 28 days, the strength reduction was 15.0% for 5% RAA, 26.9% for 10% RAA, 37.3% for 15% RAA, and 53.0% for 20% RAA and figure: 5 shows the compressive strength variation of after 07 days.

The 5% RAA mix still achieved a 28-day compressive strength of 27.87 N/mm², which exceeds the Grade 25 requirement of 25 N/mm². This indicates that up to 5% of conventional coarse aggregate can be replaced with RAA without compromising the strength requirements for rigid pavement applications.

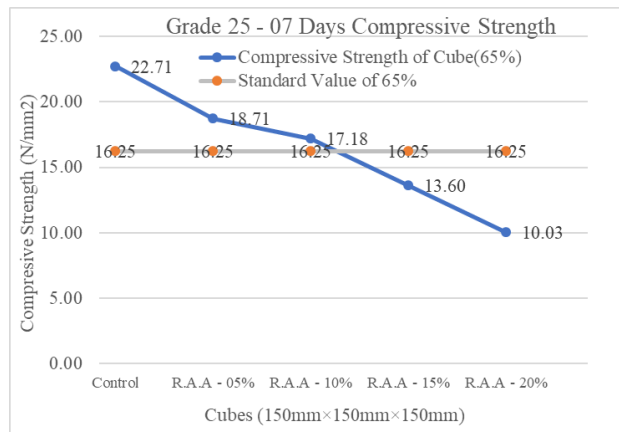


Figure 5: Compressive Strength Variation with RAA After 07 Days

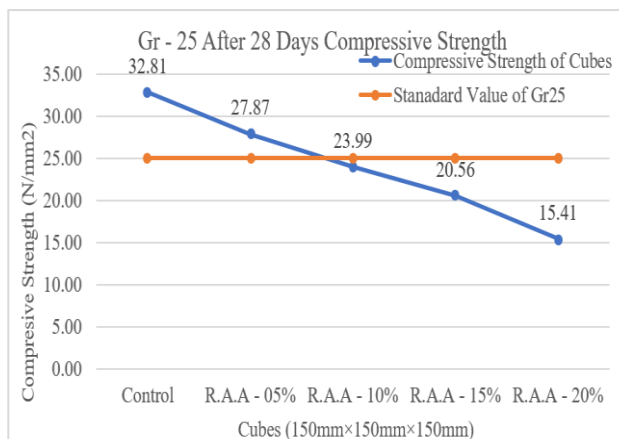


Figure 6: Compressive Strength Variation with RAA % After 28 Days

4.2.3. Flexural Strength

The flexural strength test results showed that the 5% RAA mix achieved an average flexural strength of 4.147 MPa, which is 8.8% lower than the control mix (4.549 MPa). However, it is important to note that the flexural strength of the 5% RAA mix is still within acceptable limits for rigid pavement applications.

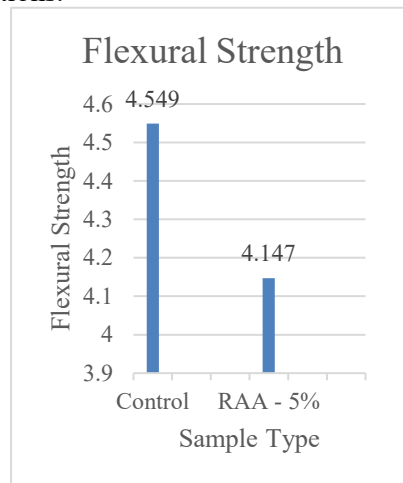


Figure 7: Flexural Strength Variation

4.2.4. SEM Test

The analysis started with an examination of the surface texture and morphological characteristics of the samples. The virgin concrete samples displayed relatively dense and compact surfaces, typically consisting of block-like or granular particles with limited presence of elongated or thread-like formations. In comparison, the concrete containing 5% recycled asphalt aggregates presented a noticeably different microstructural pattern. The images revealed a higher occurrence of needle-like (acicular) formations and loosely arranged fibrous clusters, particularly concentrated in the central portions of the observed areas. These structures often appeared as radiating crystal formations, which may indicate modifications in the hydration products or microstructural development resulting from the incorporation of RAA.

The SEM analyses were conducted at multiple magnifications (0.1KX, 0.5KX, 1KX, 5KX, and 10KX) to examine both detailed surface characteristics and the overall morphology. Figures 8, 9, 10, and 11 illustrate the differences between the two samples: the virgin aggregate is displayed on the left, while the RAA sample with the optimal replacement percentage is shown on the right.

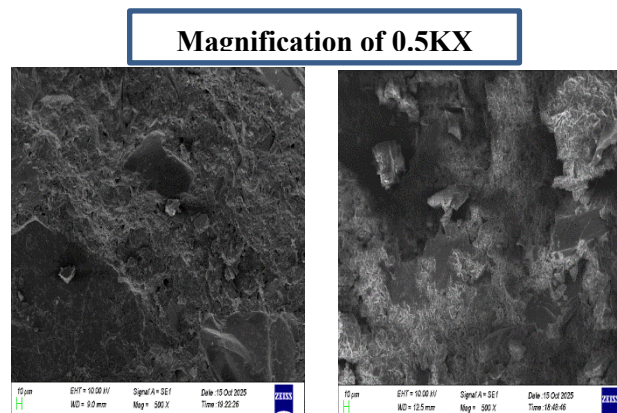


Figure 8: Magnification of 0.5KX Virgin VS Optimum %

Magnification of 1.0KX

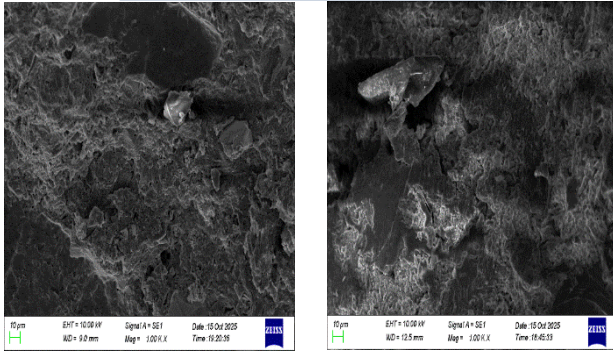


Figure 9: Magnification of 1.0KX Virgin VS Optimum

Magnification of 5.0KX

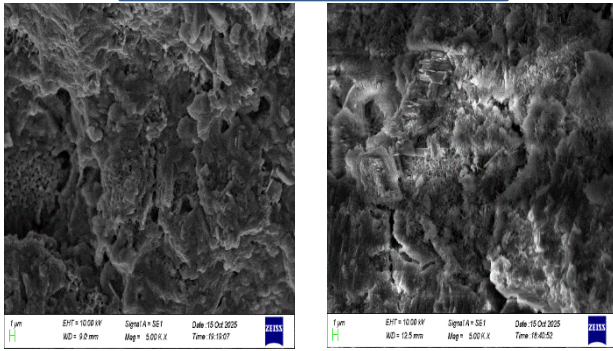


Figure 10: Magnification of 5.0KX Virgin VS Optimum %

Magnification of 10.0KX

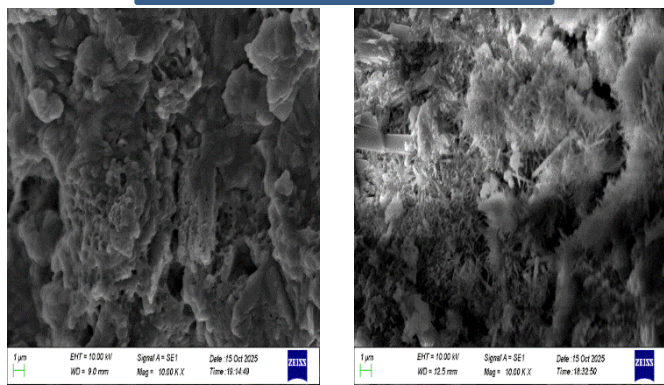


Figure 11: Magnification of 10.0KX Virgin VS Optimum %

5. Concluding Discussion

The primary objective of this study was to assess if recycled asphalt aggregates (RAA) could be used to partially substitute natural coarse aggregates while maintaining the concrete’s strength and overall quality.

The physical and mechanical characteristics of recycled asphalt aggregates (RAA) indicate that they are generally appropriate for use in concrete. Although the presence of an asphalt coating on the RAA

surface leads to slightly lower strength compared to natural aggregates, incorporating RAA at a 5% replacement level still allowed the concrete to meet the standards set by ICTAD.

Results from the compressive strength tests showed that concrete containing 5% RAA reached 27.87 N/mm² after 28 days, exceeding the minimum requirement for Grade 25 concrete. The flexural strength of this mix was measured at 4.147 MPa, which is only marginally lower than that of the control mix at 4.549 MPa. Additionally, the workability of the 5% RAA mix remained within the acceptable limits for rigid pavement applications.

SEM analysis indicated that even a modest addition of RAA, such as 5%, can noticeably influence the microstructure of concrete. For use in pavements, these microstructural changes could offer benefits if the RAA content is carefully optimized. However, further testing of mechanical performance and durability is necessary to fully verify the practical advantages of this approach.

The study indicates that replacing 5% of natural coarse aggregates with RAA represents the optimal level. Exceeding this proportion leads to reductions in both compressive and flexural strength below the required standards. Implementing a 5% RAA replacement provides a sustainable approach to road construction by lowering the demand for natural aggregates and helping to reduce asphalt waste.

The RAA can be safely used in rigid pavement concrete up to 5% replacement without compromising strength or quality

References

- Dulce, V. G.-O. et al., 2023. Application of Recycled Asphalt Pavement Aggregate in Rigid Pavement. *Journal of Building Technology*, 5(2), pp. 1-13.
- Eric , C. F. et al., 2014. Fracture Properties of Roller-Compacted Concrete with Virgin and Recycled Aggregates. *Transportation Research Record: Journal of the Transportation Research Board*, 2441(1), pp. 128-138.
- Ines, B., Saloua, E. E. K. & Jamel, N., 2018. Experimental testing and modelling of roller compacted concrete incorporating RAP waste as aggregates. *European Journal of Environmental and Civil Engineering*, pp. 1-21.
- Institute for Construction Training and Development (ICTAD), 2009. *Standard Specifications for Construction and Maintenance of Roads and Bridges*. 2nd Edition ed. Colombo: s.n.
- Jaime, R. R.-V. et al., 2024. A Review of Sustainable Pavement Aggregates. *Applied Sciences*, 14(16), p. 7112.
- Kavitha , K., Saravanan , K. & Goutham, S., 2023. Perspectives on the utilization of reclaimed asphalt pavement in concrete pavement construction: A critical review. *Case Studies in Construction Materials*, Volume 19.
- Manpreet, S. et al., 2020. Feasibility Study on Use of Washed-Reclaimed Asphalt as a Partial Replacement of Natural Aggregate in Dry-Lean Concrete as Base Course for Rigid Pavement. *Journal of Materials in Civil Engineering*, 32(7).
- Mostafa, A., Abolfazl, k., Amin, A. & Hamed, R., 2017. Influence of high content of reclaimed asphalt on. *International Journal of Pavement Engineering*, pp. 1-11.
- Salim, A.-O., Hossam, F. & Abdulwahid, H., 2009. Recycling of Reclaimed Asphalt Pavement in Portland Cement Concrete. *The Journal of Engineering Research*, 6(1), pp. 37-45.
- Surender , S., G.D.R.N, R. & Praveen, K., 2017. Feasibility study of RAP aggregates in cement concrete pavements. *Road Materials and Pavement Design*, pp. 1-20.
- Surender , S., Kumari, M. & G., D. R., 2019. Laboratory investigation of RAP for various layers of flexible and concrete pavement. *International Journal of Pavement Engineering*, pp. 1-13.
- Surya, K. S. et al., 2020. Reclaimed Asphalt Pavement as a Substitution to Natural Coarse Aggregate for the Production of Sustainable Pervious Concrete Pavement Mixes. *Journal of Materials in Civil Engineering*, 32(11).

ICRES26_044

**VEGETATION DYNAMICS AS AN INDICATOR OF RESOURCE EFFICIENCY
AND SUSTAINABLE URBAN PLANNING: A COMPARATIVE GIS-BASED STUDY
OF SELECTED URBAN AND PERI-URBAN AREAS IN AMPARA DISTRICT, SRI
LANKA****M.A.D.N. Randeepanee, R.P.I.N. Imasha, L.A.W.C. Liyanage, K.A.S.H. Wijayasenarathne*,
P.B.M.K.D.C.S. Basnayaka, R.M.A. Dilini***Sri Lanka Technology Campus, Ingiriya Road, Padukka, Sri Lanka***Correspondence E-mail: harshaniwi@sltc.ac.lk, TP: +94716674566*

Abstract: Rapid urbanization in developing regions is increasing pressure on vegetation, ecosystem services, and the sustainable use of natural resources. Understanding how urban growth affects green cover over time is therefore essential for promoting resource-efficient urban development. This study examines vegetation dynamics as an indicator of sustainable urban growth through a comparative analysis of Ampara City and the peri-urban Lahugala area in the Ampara District, Sri Lanka, using GIS and remote sensing techniques. Multi-temporal Landsat 8 imagery from 2014 to 2023 was used to derive the Normalized Difference Vegetation Index (NDVI) and the Normalized Difference Built-up Index (NDBI), enabling the assessment of long-term changes in vegetation cover and built-up expansion. Pearson correlation analysis was applied to evaluate the relationship between vegetation dynamics and urban development. The results reveal a consistently strong and statistically significant inverse relationship between NDVI and NDBI in both areas ($r = -1.000$, $p < 0.01$), indicating that vegetation decline is closely associated with increasing built-up areas rather than short-term environmental fluctuations. Ampara City shows relatively stable vegetation conditions with occasional recovery periods, suggesting that structured land management, ongoing agricultural activities, and localized greening initiatives may help offset some impacts of urban expansion. In contrast, Lahugala exhibits greater year-to-year variation in vegetation cover, highlighting the sensitivity of peri-urban landscapes located near protected areas to even small-scale human disturbances. Overall, the findings demonstrate that the integrated NDVI–NDBI approach provides a practical framework for detecting vegetation loss, monitoring urban environmental pressure, and supporting resource-efficient and climate-resilient urban planning in rapidly developing tropical regions.

Keywords: Vegetation dynamics; Urban expansion; NDVI; NDBI; Sustainable urban planning; Remote sensing and GIS

1. Introduction

Urban growth is a complex and multidimensional process that extends beyond the physical expansion of cities. It involves profound socio-economic transformations, including rising population densities, increasing economic activity, and significant shifts in land use and resource consumption (Clark, 1982). Urban centres often act as key drivers of regional and national development because they concentrate infrastructure, skilled labour, and service networks that support economic efficiency and productivity. The spatial clustering of economic activities within cities also encourages innovation, specialization, and diversity, reinforcing the central role of urban areas in modern development pathways (Uduporuwa et al., 2025).

Despite these benefits, the rapid and frequently unplanned nature of urbanization has intensified pressure on land, water, energy, and ecological resources. Such pressures have raised important concerns regarding sustainability and resource efficiency in urban planning. As cities expand, natural landscapes are increasingly transformed into built environments, often leading to significant changes in vegetation cover and ecosystem functioning. Understanding how urban growth affects natural systems—particularly urban vegetation—has therefore become essential for developing more sustainable planning strategies. In this context, the present study investigates vegetation dynamics in relation to urban expansion in selected urban and peri-urban areas of the Ampara District in Sri Lanka, with the aim of evaluating how spatial indicators of vegetation cover and built-up development can inform resource-efficient urban planning.

At the global scale, urban expansion is closely associated with environmental change, primarily through the conversion of natural ecosystems and landscapes into built infrastructure (Lu et al., 2019; Viana et al., 2019). These transformations, largely driven by human activities, contribute significantly to environmental degradation, habitat fragmentation, and disruptions to natural ecological processes. Urbanization is continuing to accelerate worldwide. In 2019, more than half of the global population—around 4.2 billion people—lived in urban areas, and this number is projected to approach nearly 6 billion by 2041 (Uduporuwa et al., 2025). Within this rapidly urbanizing context, vegetation plays a critical role in maintaining ecological balance. Urban greenery helps regulate microclimates, reduce flood risks, conserve biodiversity, and mitigate the Urban Heat Island (UHI) effect (Arachchi, 2023). Consequently, monitoring vegetation dynamics has become an increasingly important component of urban sustainability assessments and land-use planning.

These challenges are particularly evident in developing regions, where rapid urban growth is often accompanied by rising energy demand and growing environmental stress. Cities are estimated to account for approximately 60–80% of global energy consumption and contribute a similar proportion of global CO₂ emissions (Polydoros and Cartalis, 2015). In non-OECD regions of Asia and Africa, continued urban expansion is expected to further increase emissions, largely due to reliance on carbon-intensive energy systems in transportation and the built environment (Polydoros and Cartalis, 2015). At the same time, urban areas are becoming increasingly vulnerable to intensified heat waves associated with the Urban Heat Island effect. The expansion of impervious surfaces and the widespread use of construction materials such as concrete and asphalt can elevate urban temperatures several degrees above surrounding rural areas. This temperature increase contributes to higher cooling energy demand and can also intensify heat-related health risks (Polydoros and Cartalis, 2015). These trends highlight the importance of integrating vegetation-based strategies into urban planning to enhance thermal comfort, reduce energy consumption, and strengthen overall urban resilience.

Within Sri Lanka, the Ampara District in the Eastern Province provides a particularly relevant setting for examining vegetation dynamics in the context of emerging urban growth. The district contains ecologically important protected areas, including Gal Oya and Kumana National Parks, which provide vital ecosystem services and serve as habitats for many endemic and migratory species. At the same time, ongoing urban development, agricultural expansion, and population growth are gradually transforming surrounding landscapes, particularly in and around Ampara City and nearby areas such as Lahugala. With a population density of approximately 180 persons per km² (Department of Census and

Statistics, 2022), the district exhibits diverse land-use patterns that offer useful opportunities for examining interactions between urban development and environmentally sensitive ecosystems. Investigating developing urban landscapes such as Ampara—rather than already highly urbanized metropolitan areas like Colombo—also allows researchers to evaluate early planning interventions aimed at preserving vegetation, reducing surface warming, and promoting sustainable urban growth before irreversible environmental degradation occurs.

Within this local context, Ampara City functions as a rapidly developing administrative and economic centre experiencing increasing urban pressure, while Lahugala, located near Lahugala–Kithulana National Park, retains relatively extensive natural vegetation and serves as an important peri-urban buffer landscape. The contrast between these two areas provides a valuable opportunity to examine vegetation dynamics across different stages of urbanization and to generate insights that may support sustainable and resource-efficient planning in regions bordering protected ecosystems.

Remote sensing techniques offer effective tools for monitoring these environmental changes over time. The Normalized Difference Vegetation Index (NDVI) is widely used to assess vegetation density and health, with higher values indicating dense vegetation and lower values representing sparsely vegetated or non-vegetated surfaces (Sun et al., 2019). In contrast, the Normalized Difference Built-up Index (NDBI) is commonly applied to identify built-up areas, where higher values correspond to greater coverage of impervious surfaces (Asyraf et al., 2020; Thakur and Jaswal, 2025). When used together, NDVI and NDBI improve the ability to distinguish between vegetated and developed land surfaces (Yasin et al., 2021; Guha et al., 2018; Zha et al., 2003). Correlation analysis between these indices also allows for a quantitative assessment of the relationship between vegetation cover and built-up intensity, providing statistical evidence of how urban expansion influences green spaces and supporting more informed urban planning decisions (Thakur and Jaswal, 2025).

Overall, studies of vegetation dynamics using NDVI and NDBI offer a robust analytical framework for supporting resource-efficient urban planning. By identifying areas experiencing vegetation decline and rapid built-up expansion, planners and policymakers can prioritize strategies such as green infrastructure development, zoning regulations, and ecosystem conservation. These measures can help mitigate Urban Heat Island effects, regulate microclimates, enhance biodiversity, and improve long-term urban sustainability. Early assessments in developing urban landscapes such as Ampara are particularly valuable because they enable proactive planning measures aimed at preserving vegetation and managing urban growth more sustainably, thereby reducing future warming, energy demand, and environmental degradation.

2. Methodology

2.1. Study Area

The study was carried out in Ampara City (7°17'30" N, 81°40'20" E) and Lahugala (6°52'22" N, 81°43'21" E) in the Ampara District of Sri Lanka. These two locations were selected because they represent different land-use characteristics and levels of urban development within the district. Ampara City is a rapidly developing administrative and commercial center that has experienced notable changes in population, infrastructure development, and land use over the past decades. In contrast, Lahugala is largely rural and is located near the Lahugala–Kithulana National Park, an ecologically important protected area dominated by forest vegetation and natural habitats. The selection of these two sites allowed a comparison of vegetation conditions between urban and peri-urban environments, helping to understand how increasing urbanization may influence vegetation health and land-cover patterns. Similar remote sensing and GIS approaches have been widely used to analyze vegetation dynamics and urban expansion in heterogeneous landscapes (Weng, 2012; Singgalen, 2023).

2.2. Data Collection

Satellite imagery and related spatial data used in this study were obtained from the United States Geological Survey (USGS) Earth Explorer database. The analysis was based primarily on Landsat 8

satellite images, which provide multispectral data suitable for monitoring vegetation and land-cover changes over large geographic areas.

Landsat imagery has a spatial resolution of 30 meters, meaning that each pixel in the image represents an area of approximately 30 m × 30 m on the ground. This resolution is widely used in environmental and land-use studies to observe vegetation distribution and urban development patterns.

Figures 1 and 2 present the methodological workflow used in this study, illustrating the steps followed in calculating the Normalized Difference Vegetation Index (NDVI) and the Normalized Difference Built-up Index (NDBI).

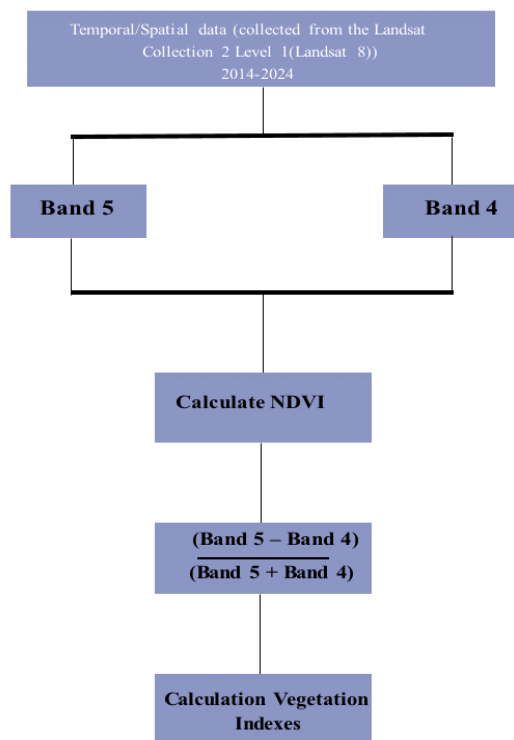


Figure 1: Process flow diagram for NDVI

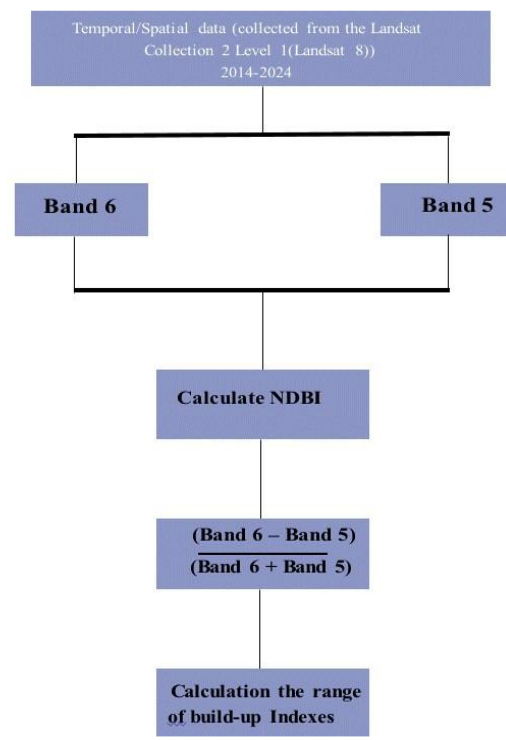


Figure 2: Process flow diagram for NDBI

2.3. Normalized Difference Vegetation Indexes (NDVI) Calculation

Vegetation conditions within the study areas were assessed using the Normalized Difference Vegetation Index (NDVI), which is one of the most commonly used indicators for evaluating vegetation density and health using satellite imagery. Healthy vegetation reflects near-infrared (NIR) radiation strongly while absorbing red light for photosynthesis. NDVI uses this difference in reflectance to estimate the presence and condition of vegetation.

The analysis was conducted using ArcGIS software (version 10.8). Landsat 8 spectral bands were used to calculate the index, specifically Band 5 (Near Infrared) and Band 4 (Red). The NDVI layer was generated using these bands as part of the vegetation analysis (Singgalen et al., 2023).

$$NDVI (Land Sat 08) = (IR \text{ Band } (5) - R \text{ Band } (4)) / (IR \text{ Band } (5) + R \text{ Band } (4)) \quad (1)$$

Where,

NIR = Near Infrared Radiance R = Red Band

NDVI values generally range between -1 and +1. Higher NDVI values indicate dense and healthy vegetation, while values close to zero represent sparse vegetation or bare soil, and negative values typically correspond to water bodies or non-vegetated surfaces.

2.4. Normalized Different Built-up Indexes (NDBI) Calculation

Based on the SWIR band 6 and NIR band 5 used as data makeup and modified to NDBI analysis, built-up indexes were obtained to determine the relationship between the LST and NDBI development procedure (Singgalen et al., 2023).

$$\text{NDBI} = (\text{SWIR Band (6)} - \text{NIR Band (5)}) / (\text{SWIR Band (6)} + \text{NIR Band (5)}) \quad (2)$$

Where,

NIR = Near Infrared Radiance

SWIR = Short Wave Infrared Radiance

The resulting NDVI and NDBI raster images corresponding to the study areas were generated for further analysis. These index values typically fall within the range of -1 to $+1$. Higher NDBI values are generally associated with urban infrastructure and built-up areas, while lower values represent vegetation, water bodies, or bare land.

The classification of land-cover types was carried out through visual interpretation and clustering of the resulting index images. Areas with higher NDBI values were identified as built-up surfaces, while areas with lower values were classified as non-built-up land covers, including vegetation and bare soil (Ullah et al., 2023).

2.5 Correlation analysis

Pearson correlation analysis was used to examine the relationship between vegetation cover and built-up intensity by analysing NDVI and NDBI values extracted from raster datasets. In this analysis, each $30 \text{ m} \times 30 \text{ m}$ raster pixel within the study area was treated as an observation unit, allowing the results to represent the spatial variability of vegetation and built-up surfaces across the entire study area. In this study, NDVI was used to represent vegetation density and health, while NDBI was used to indicate the extent of built-up surfaces, including buildings and road infrastructure. The Pearson correlation coefficient (r) was used to measure the strength and direction of the relationship between the two variables, with values ranging from -1 to $+1$. Values closer to -1 indicate a strong inverse relationship, meaning that vegetation cover tends to decrease as built-up intensity increases, whereas values closer to zero indicate a weak or negligible linear relationship.

3. Discussion

3.1. Normalized Different Vegetation Indexes (NDVI) in Ampara City

The NDVI mean values for Ampara city from 2014 to 2023 show significant interannual variations, reflecting changes in vegetation cover over the decade(Figure 3).

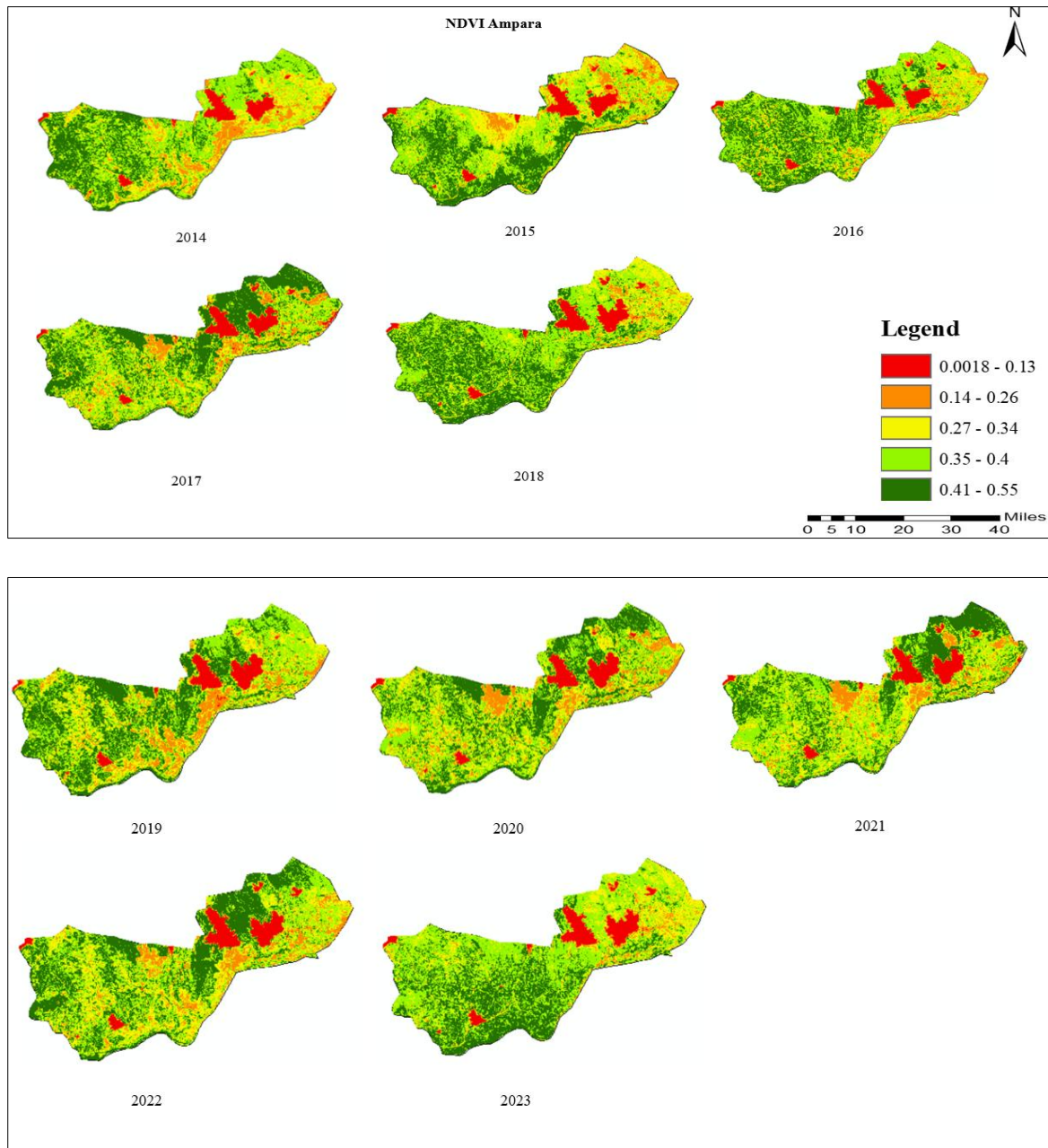


Figure 3: NDVI analysis in Amapara city

In 2014, the NDVI was 0.433, indicating moderate vegetation health, but in 2015 it decreased slightly to 0.399. A recovery was observed in 2016 (0.444) and continued until 2017 (0.475), indicating improved greenness and vegetation density. The highest NDVI was recorded in 2018 (0.510) and remained high in 2019 (0.508), possibly due to favorable climatic conditions or increased vegetation cover. However, since 2020, NDVI values have shown a declining trend, falling to 0.477 in 2020 and 0.418 in 2021. There was a slight improvement in 2022 (0.481), but the lowest value of the decade was observed in 2023 (0.368), indicating a decline in vegetation health. These fluctuations may be associated with seasonal rainfall variability, land use changes, or anthropogenic pressures, highlighting the importance of monitoring vegetation dynamics for sustainable land management in Ampara City.

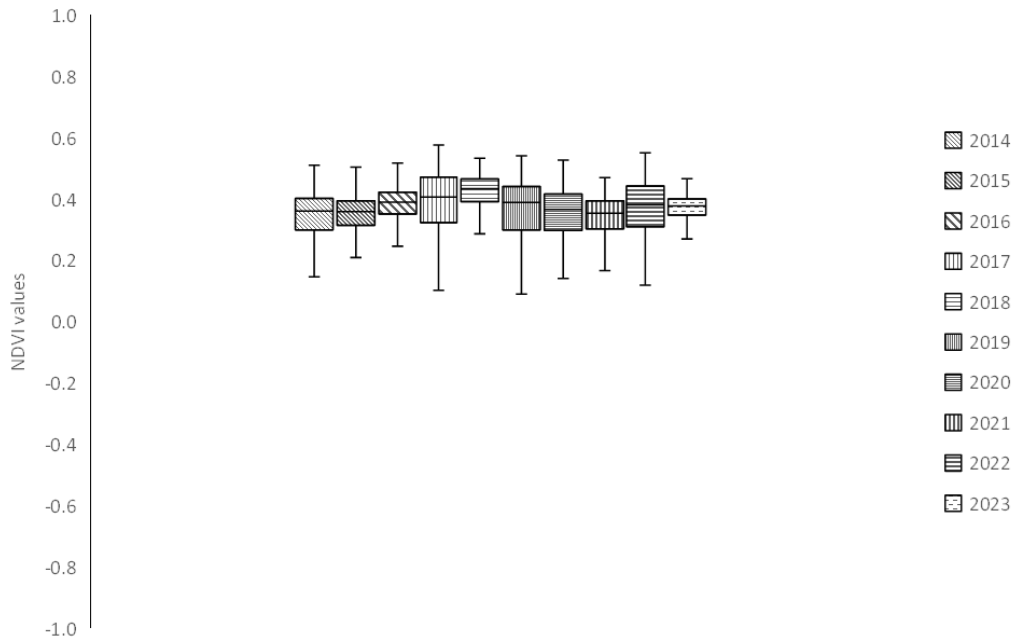
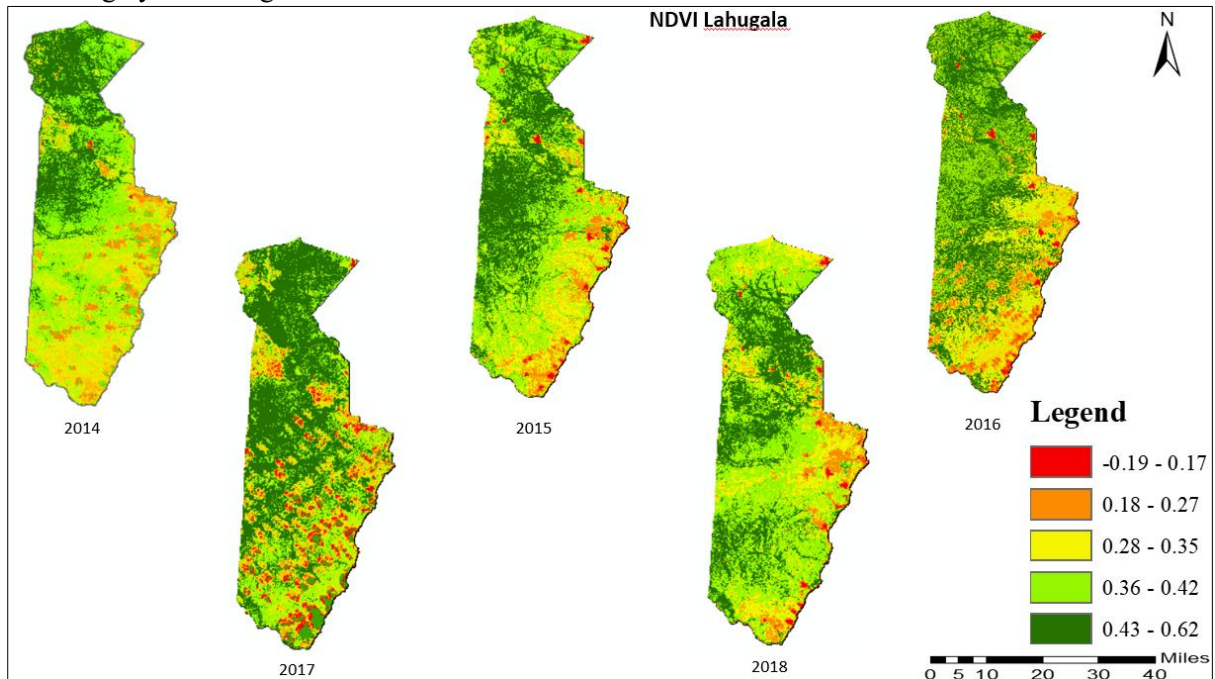


Figure 4: NDVI value descriptive statistics in Ampara City

3.2. Normalized Different Vegetation Indexes (NDVI) in Lahugala Area

The NDVI mean values for Lahugala from 2014 to 2023 show considerable year-to-year fluctuations, reflecting dynamic vegetation conditions in the area.



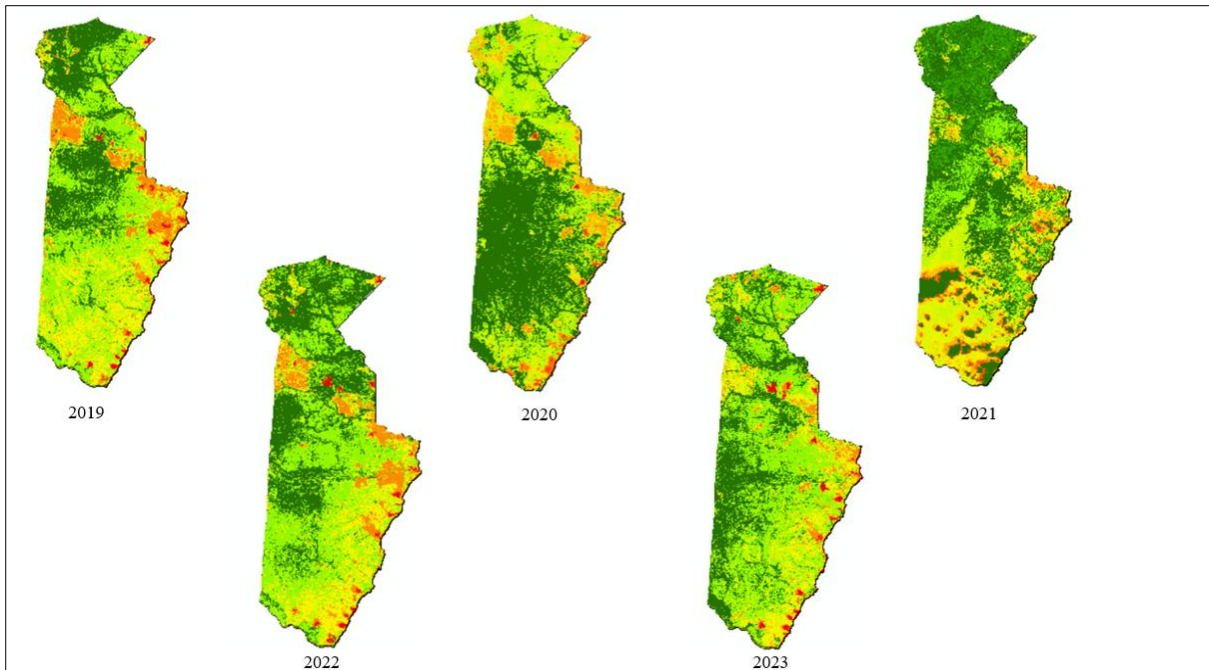


Figure 5 : NDVI analysis in Lahugala area

In 2014, the NDVI was 0.279, indicating moderate vegetation cover, but it declined in 2015 (0.226) and remained relatively low in 2016 (0.235). A notable increase occurred in 2017, reaching 0.303, suggesting improved vegetation health. However, in 2018, NDVI dropped again to 0.245, before recovering to 0.280 in 2019. A slight decrease was seen in 2020 (0.269), followed by a further reduction to 0.213 in 2021, marking one of the lowest points in the decade. In 2022, NDVI values rose sharply to 0.304, the highest in the series, before slightly decreasing to 0.281 in 2023. The box plot illustrates these variations in certain years (e.g., 2014, 2017, 2021) indicating higher variability in vegetation conditions. These fluctuations could be influenced by seasonal rainfall patterns, drought events, and anthropogenic factors such as agricultural expansion or deforestation, underlining the need for targeted vegetation management and conservation in Lahugala.

Given its ability to provide a precise and quantitative analysis of the strength, mass, and geographical distribution of vegetation, NDVI was selected as a key indicator for this study. NDVI is particularly valuable for analyzing changes in vegetation patterns over time, detecting degradation, and assessing the impact of climate and human factors on vegetation (Han et al., 2022). NDVI is a critical tool for analyzing changes in vegetation patterns over time, detecting degradation, and assessing the impact of climate and human factors on vegetation. NDVI is particularly valuable for analyzing changes in vegetation patterns over time, detecting degradation, and assessing the impact of climate and human factors on vegetation in regions such as Lahugala that are proximal to protected forests. Thus, by enabling the assessment of vegetation patterns in relation to human influence and environmental variability.

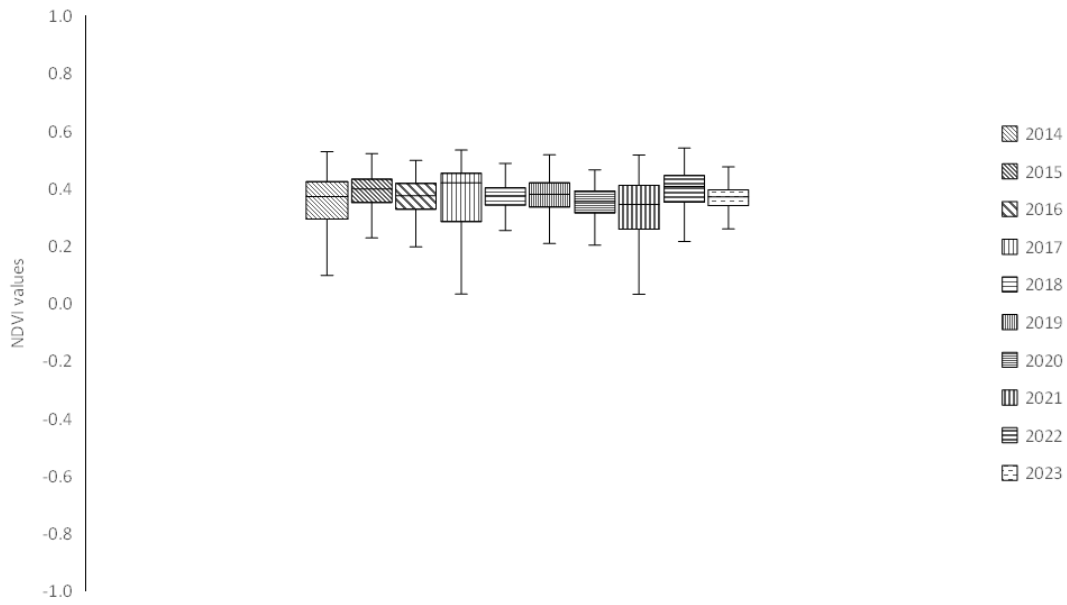
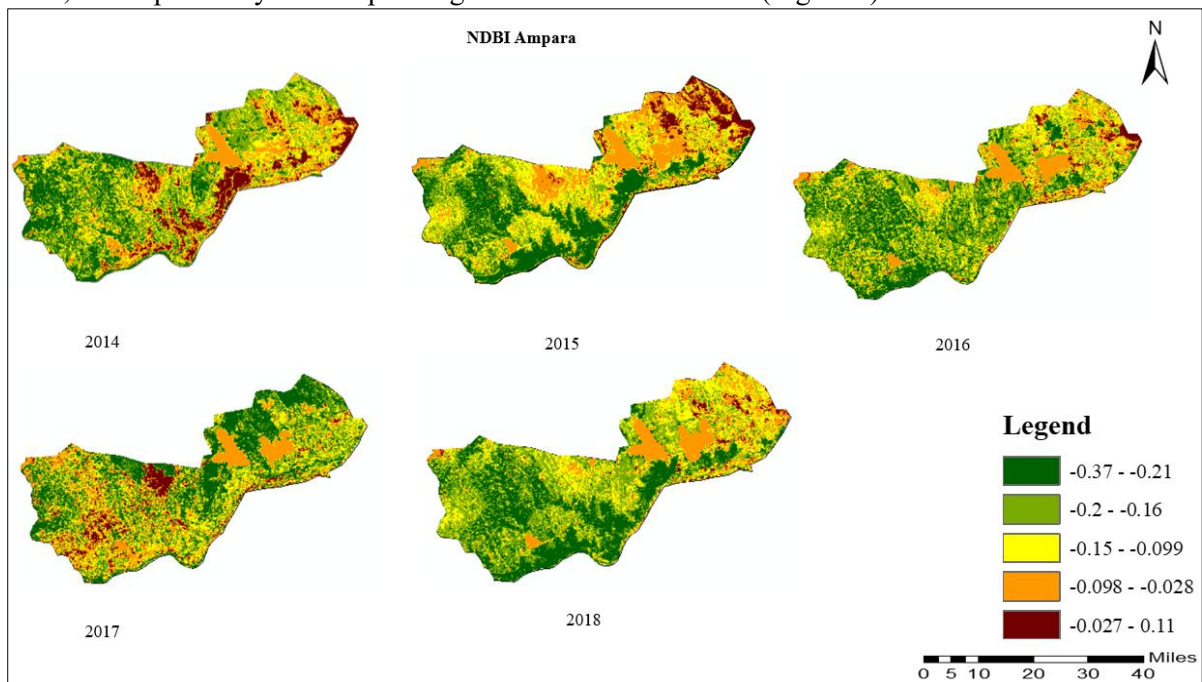


Figure 6 : NDVI value descriptive statistics in Lahugala area

3.3. Normalized Different Built-up Indexes (NDBI) in Ampara City

Based on the provided data, Ampara showed a general trend of decreasing NDBI values from 2014 to 2023, accompanied by a corresponding increase in NDVI values(Figure 7).



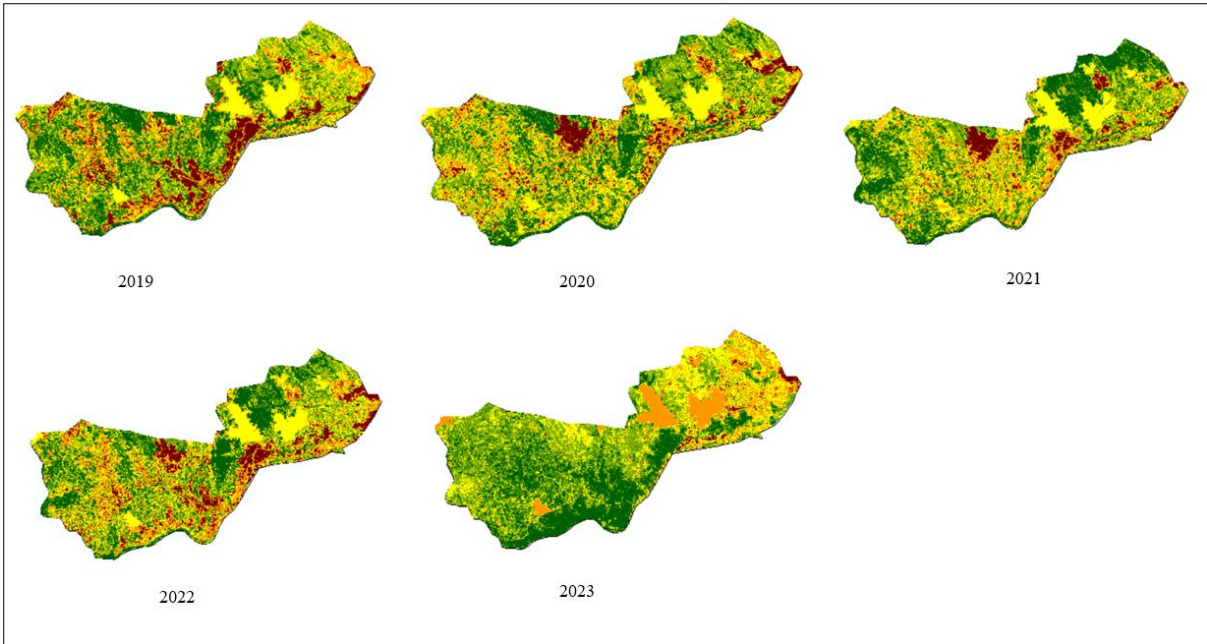


Figure 7: NDBI – Analysis results in Ampara city

This suggests a decrease in built-up areas and an increase in vegetation over the decade. The NDBI values for Ampara ranged from -0.2239 to -0.1610, with an average of -0.2291. The NDVI values for Ampara ranged from 0.3682 to 0.5099, with an average of 0.4578. The graph illustrates the inverse relationship between these two indices, showing that as NDBI decreases, NDVI increases.

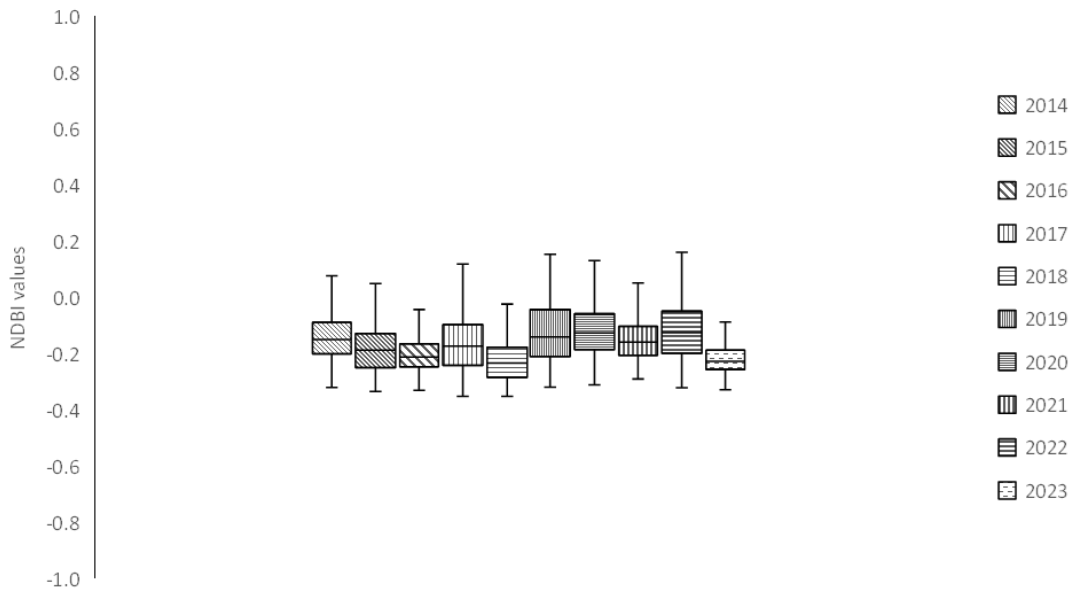


Figure 8: NDBI value descriptive statistics in Ampara City

3.4. Normalized Different Built-up Indexes (NDBI) in Lahugala Area.

Lahugala exhibited a different pattern compared to Ampara. While the NDBI values for Lahugala were generally negative, indicating a predominantly vegetated area, there was a less pronounced trend of change over the decade.

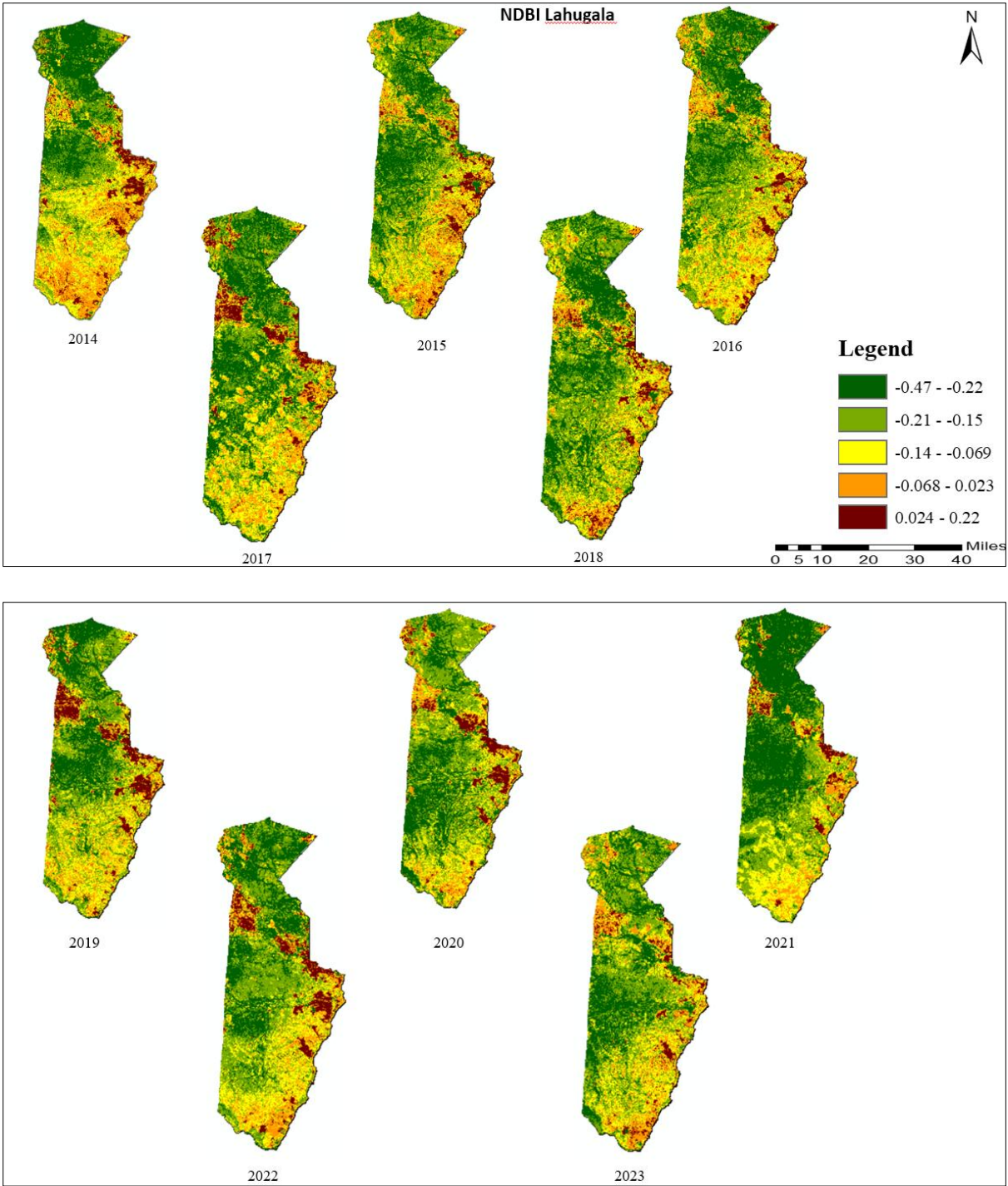


Figure 9: NDBI – Analysis results in Lahugala area

The NDBI values for Lahugala ranged from -0.2646 to 0.0041, with an average of -0.1770. The NDVI values for Lahugala ranged from 0.1217 to 0.4939, with an average of 0.3541. Similar to Ampara, there is an inverse relationship between NDBI and NDVI, but the changes in both indices are more variable.

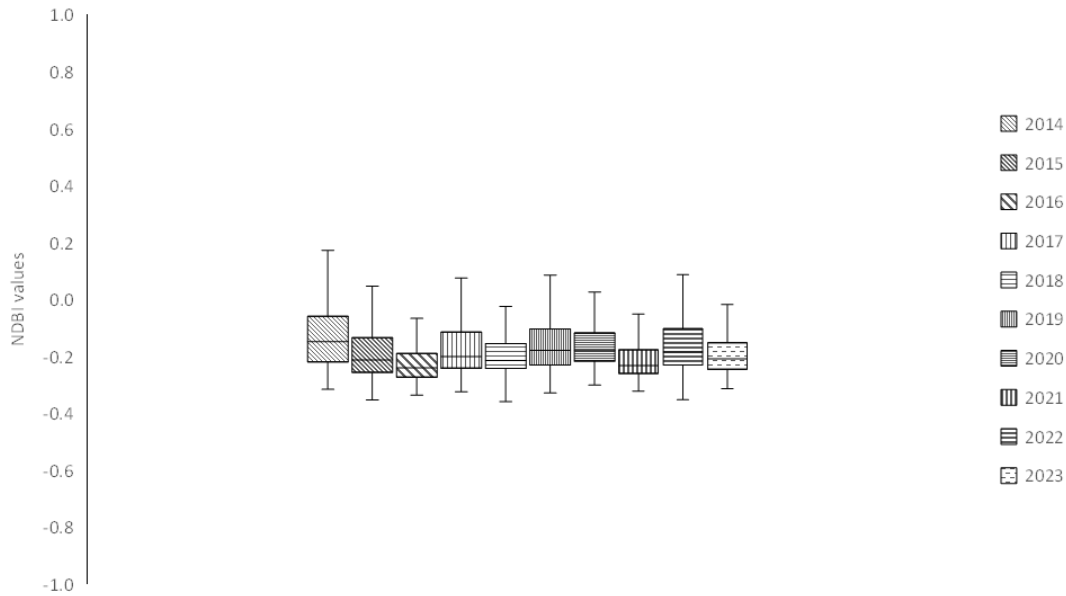


Figure 10: NDBI value descriptive statistics in Lahugala Area

3.5. Correlation between NDBI and NDVI in Ampara city and Lahugala peri-urban area

The present study demonstrates a consistently very strong and statistically significant inverse relationship between vegetation cover and built-up intensity in both Ampara City and Lahugala during 2014–2023, with Pearson correlation coefficients of $r = -1.000$ ($p < 0.01$). This indicates that vegetation dynamics and built-up expansion are tightly coupled and systematically linked to land-cover transformation processes rather than random variation (Weng, 2012). Spatial analyses further confirmed that high NDBI values correspond to low NDVI values, highlighting the concentration of built-up surfaces in areas where vegetation has declined, while low NDBI areas retain higher vegetation cover. Although similar spatial relationships were observed in both regions, Lahugala exhibited greater inter-annual variability due to dynamic land-use activities, emphasizing the ecological sensitivity of buffer zones near protected ecosystems (Gill et al., 2007; Ullah et al., 2023; Dahanayake et al., 2024).

Temporal trends revealed distinct dynamics between the two regions. Ampara City exhibited high temporal stability, with consistently higher NDVI and lower NDBI values than Lahugala, indicative of structured and gradual land-cover transformation. Periods of vegetation recovery even when NDBI remained stable suggest that vegetation dynamics are influenced not only by urban expansion but also by local land management practices, conservation initiatives, urban greening efforts, and maintenance of agricultural patches (Altiner & Bingöl, 2025; Bowler et al., 2010; Weng, 2012). Minor declines in NDVI between 2019 and 2023, despite stable NDBI values, likely reflect climatic variability (e.g., rainfall and temperature anomalies) and localized land-use activities, including seasonal agriculture, shifting cultivation, or peri-urban management practices (Singgalen, 2023; Alademomi et al., 2022). Similar patterns have been observed in other studies: Altiner & Bingöl (2025) reported that targeted green-space preservation maintained NDVI values in rapidly urbanizing zones; the Bhopal study documented vegetation recovery in previously barren areas due to reforestation or fallow land management; and Alademomi et al. (2022) found that NDVI variations in Lagos were influenced not only by urban expansion but also by transitions from wetlands and bare land to mixed vegetation. Collectively, these findings indicate that even in areas experiencing moderate urbanization, vegetation cover responds to a combination of ecological, climatic, and anthropogenic factors, emphasizing the importance of context-specific land management in sustaining urban ecosystem services.

These results align closely with Altiner and Bingöl (2025), who showed that preserved urban green spaces maintain higher NDVI values and reduce land surface temperature (LST), whereas conversion of vegetated areas into built-up spaces increases NDBI and LST, highlighting the importance of urban

green infrastructure in mitigating heat and maintaining ecological balance. Similarly, the Bhopal study reported strong correlations between LST and NDBI and negative correlations between NDVI and LST, showing that built-up expansion drives surface warming while vegetation loss exacerbates urban heat island effects. In Lagos, Alademomi et al. (2022) demonstrated that conversion of mixed vegetation and bare land to built-up areas increased NDBI and LST and decreased NDVI, further supporting the generalizability of the inverse vegetation–built-up relationship across tropical urban landscapes.

Spatial analysis further corroborates these findings. In Ampara City, high NDBI values correspond to low NDVI values, indicating that built-up areas are concentrated in zones where vegetation cover has been diminished. Areas characterized by low NDBI retain comparatively high NDVI values, suggesting that urban expansion remains spatially constrained and vegetation persists in discrete patches. In Lahugala, although a similar inverse spatial relationship is observed, the distribution of vegetation and built-up areas is less uniform due to dynamic land-use patterns. Even small increases in built-up surfaces in Lahugala are associated with measurable declines in vegetation, emphasizing the vulnerability of peri-urban and buffer landscapes to incremental anthropogenic pressures (Ullah et al., 2023; Dahanayake et al., 2024).

Temporal trends reveal distinct dynamics between the two regions. Ampara City exhibits high temporal stability, with consistently higher NDVI and lower NDBI values than Lahugala, indicative of a structured and gradual land-cover transformation. Notably, periods of vegetation recovery are observed even when NDBI remains negative or stable, suggesting that vegetation dynamics are influenced not only by urbanization but also by factors such as land management practices, agricultural persistence, or local conservation initiatives. For instance, between 2019 and 2023, minor declines in NDVI despite stable NDBI values indicate the combined influence of climatic variability and land-use practices on vegetation patterns. In contrast, Lahugala displays higher inter-annual variability, reflecting the dynamic nature of peri-urban and rural landscapes where seasonal agriculture, shifting cultivation, and localized settlement expansion drive rapid but often transient changes in vegetation cover (Singgalen, 2023). Nevertheless, the consistently strong inverse correlations demonstrate that vegetation responds systematically to land-surface modifications, emphasizing the high ecological sensitivity of areas adjacent to protected ecosystems.

From a planning and environmental governance perspective, the findings of this study provide important insights for guiding sustainable urban development strategies in Ampara District. The consistently strong inverse relationship observed between NDVI and NDBI indicates that vegetation dynamics are closely associated with the spatial expansion of built-up areas. This pattern confirms that vegetation decline is closely linked to land-cover transformation driven by urban development. As a result, these findings highlight the importance of adopting planning approaches that balance urban growth with ecological sustainability.

In Ampara City, the gradual increase in NDVI together with the declining trend in NDBI suggests that opportunities exist for relatively controlled and environmentally sensitive urban expansion. The persistence of vegetation patches within the urban landscape indicates that integrating green infrastructure into development planning can help maintain ecological functions while accommodating urban growth. Municipal planning authorities could therefore consider implementing spatial zoning mechanisms that distinguish clearly between built-up development zones, agricultural preservation areas, and ecological conservation zones. Areas with relatively high vegetation density should be protected from uncontrolled land conversion, while restrictions on deforestation and fragmentation of remaining green spaces should be incorporated into land-use policies. Urban ecological planning should also prioritize the preservation and expansion of green infrastructure. Increasing the availability of urban green spaces, including public parks, roadside tree corridors, and urban forestry networks, can significantly enhance ecosystem service provision. Vegetation within cities plays an important role in regulating local microclimates, improving air quality, and reducing urban heat accumulation, while also contributing to carbon sequestration and improved urban livability (Bowler et al., 2010).

Evidence from previous studies further demonstrates the broader environmental and economic benefits of urban vegetation. For example, a large-scale assessment conducted in California estimated that existing urban trees reduce annual air-conditioning energy consumption by approximately **2.5 %**, while peak electricity demand can decline by nearly 10 %, resulting in substantial economic savings for utilities and households (McPherson and Simpson, 2003). Similarly, modelling-based research carried out in Cairo found that increasing urban tree coverage in densely built environments can lower air temperatures by about 0.2–0.4 K, which contributes to reductions in cooling energy demand and improvements in outdoor thermal comfort (Aboelata and Sodoudi, 2020). Although the magnitude of these benefits may vary depending on climatic conditions and urban density, these findings highlight the potential of vegetation-based strategies to reduce heat accumulation and support more energy-efficient urban environments. Such co-benefits provide further justification for incorporating tree-planting programs, urban forestry initiatives, and green infrastructure requirements into urban development policies.

In contrast to the relatively stable patterns observed in Ampara City, the higher interannual variability identified in Lahugala highlights the ecological sensitivity of peri-urban landscapes located close to protected ecosystems. The proximity of Lahugala to Lahugala–Kithulana National Park suggests that even relatively small increases in built-up areas could contribute to habitat fragmentation, reduced ecological connectivity, and declining ecosystem resilience. These findings underline the importance of maintaining effective buffer-zone management and implementing stricter land-use regulations in peri-urban regions. Controlled settlement expansion, protection of forest buffer zones, and land-use practices that maintain ecological integrity are therefore essential for safeguarding biodiversity and ecosystem services in landscapes located adjacent to protected areas (Gill et al., 2007).

Remote sensing studies conducted in other regions have also demonstrated the value of vegetation indices for monitoring ecological changes in protected landscapes. For example, NDVI-based monitoring carried out in the Santa Monica Mountains National Recreation Area and Channel Islands National Park revealed long-term declines in vegetation greenness in some protected areas, highlighting how surrounding environmental pressures and climate variability can influence vegetation dynamics even within conservation landscapes (Gillespie et al., 2017). Such studies demonstrate how satellite-based vegetation monitoring can detect subtle ecological changes over time and provide valuable information for conservation planning. In a similar way, continuous NDVI-based monitoring could help identify early signs of vegetation stress in peri-urban landscapes surrounding protected ecosystems such as Lahugala.

The spatial identification of vegetation-deficient zones through NDVI–NDBI analysis also provides useful guidance for nature-based planning interventions. In rapidly developing urban environments, nature-based solutions offer cost-effective strategies for addressing climate-related challenges while maintaining ecosystem services. For example, the use of green roofs and vegetated building surfaces can reduce urban heat accumulation, enhance stormwater retention, and partially compensate for ecological functions lost due to land-cover transformation (Oberndorfer et al., 2007; Santamouris, 2014). Similarly, roadside vegetation corridors and urban tree networks can enhance shading, lower surface temperatures, improve air quality, and reduce building energy demand (Bowler et al., 2010; Nowak and Heisler, 2010).

Beyond these site-specific interventions, the methodological framework applied in this study also offers a practical decision-support tool for environmental monitoring and urban planning. The integration of NDVI and NDBI derived from satellite imagery enables planners to track vegetation loss and built-up expansion in a spatially explicit manner. Such approaches can support evidence-based planning by allowing authorities to identify emerging environmental pressures, prioritize ecological restoration areas, and monitor the effectiveness of urban greening initiatives over time (Ullah et al., 2023; Dahanayake et al., 2024). Overall, the findings emphasize the need to integrate green infrastructure, ecosystem conservation, and nature-based solutions into urban development policies. Incorporating vegetation protection into land-use planning can help cities such as Ampara achieve more balanced and

resource-efficient growth while preserving ecosystem services and enhancing climate resilience. The NDVI–NDBI analytical framework therefore offers a practical tool for guiding sustainable planning in both urban and peri-urban areas.

4. Conclusion:

The findings of this study confirm that vegetation dynamics are strongly and systematically governed by built-up expansion in both urban and peri-urban landscapes of the Ampara District, as evidenced by the consistently significant inverse NDVI–NDBI relationship. The contrasting temporal responses between Ampara City and Lahugala underscore the role of structured urban development, land management practices, and conservation measures in moderating vegetation loss, while highlighting the heightened vulnerability of peri-urban and buffer-zone environments to even limited anthropogenic disturbance. The spatial identification of vegetation-deficient and high built-up intensity zones provides practical guidance for targeted green infrastructure implementation, buffer-zone protection, and nature-based solutions aimed at mitigating urban heat, regulating microclimates, and sustaining ecosystem services. By integrating multi-temporal remote sensing with quantitative correlation analysis, this study establishes NDVI–NDBI as a reliable and scalable tool for assessing environmental pressure and resource efficiency in developing urban regions. Ultimately, the results emphasize the importance of proactive, early-stage planning in rapidly urbanizing tropical contexts to prevent irreversible vegetation degradation, enhance climate resilience, and support long-term sustainable urban development.

References:

- Aboelata, A. and Sodoudi, S., 2020. Evaluating the effect of trees on UHI mitigation and reduction of energy usage in different built up areas in Cairo. *Building and Environment*, 168, p.106490.
- Alademomi, A.S., Okolie, C.J., Daramola, O.E., Akinnusi, S.A., Adediran, E., Olanrewaju, H.O., Alabi, A.O., Salami, T.J. and Odumosu, J., 2022. The interrelationship between LST, NDVI, NDBI, and land cover change in a section of Lagos metropolis, Nigeria. *Applied Geomatics*, 14(2), pp.299-314.
- Altiner, F. and Bingöl, F., 2025. Spatio-Temporal Assessment of Land Surface Temperature, Vegetation Cover, and Built-Up Areas Using LST, NDVI, and NDBI in Balıkesir, Türkiye (1985–2025). *Sustainability*, 17(20), p.9245.
- Arachchi, M., 2023. A comparison of sentinel 2 and landsat imagery in a Sri Lankan context; a case study of urban vegetation cover in the colombo divisional secretariat division in Sri Lanka using the normalized difference vegetation index (ndvi).
- Asyraf, M. S., Damayanti, A., & Dimyati, M. (2020). The effect of building density on land surface temperature (Case Study: Turikale District, Maros Regency). *IOP Conf. Series: Earth and Environmental Science*(500).
- Bowler, D. E., Buyung-Ali, L., Knight, T. M., & Pullin, A. S. (2010). Urban greening to cool towns and cities: A systematic review of the empirical evidence. *Landscape and Urban Planning*, 97(3), 147–155. <https://doi.org/10.1016/j.landurbplan.2010.05.006>
- Clark, D. (1982). *Urban Geography: An Introductory Guide*. London: Taylor & Francis.
- Gill, S. E., Handley, J. F., Ennos, A. R., & Pauleit, S. (2007). Adapting cities for climate change: The role of the green infrastructure. *Built Environment*, 33(1), 115–133. <https://doi.org/10.2148/benv.33.1.115>
- Gillespie, T.W., Ostermann-Kelm, S., Dong, C., Willis, K.S., Okin, G.S. and MacDonald, G.M., 2018. Monitoring changes of NDVI in protected areas of southern California. *Ecological indicators*, 88, pp.485-494.
- Guha S, Govil H, Dey A, Gill N. Analytical study of land surface temperature with NDVI and NDBI using Landsat 8 OLI and TIRS data in Florence and Naples city, Italy. *Eur J Remote Sens*. 2018;51(1):667-678. <https://doi.org/10.1080/22797254.2018.1474494>
- Lu, L., Weng, Q., Guo, H., Feng, S., & Li, Q. (2019). Assessment of urban environmental change using multi-source remote sensing time series (2000-2016): A comparative analysis in selected megacities in Eurasia. *Science of The Total Environment*, 684, 567-577
- McPherson, E.G. and Simpson, J.R., 2003. Potential energy savings in buildings by an urban tree planting programme in California. *Urban forestry & urban greening*, 2(2), pp.73-86.
- Oke, T. R. (1987). *Boundary Layer Climates* (2nd ed.). London: Routledge.
- Polydoros, A. and Cartalis, C., 2015. Use of Earth Observation based indices for the monitoring of built-up area features and dynamics in support of urban energy studies. *Energy and Buildings*, 98, pp.92-99.
- Singgalen, Y. A. (2023). Implementation of spatio-temporal analysis for land use management and
- Sun, R., Chen, S., Su, H., & Jin, C. M. a. N. (2019). The Effect of NDVI Time Series Density Derived from Spatiotemporal Fusion of Multisource Remote Sensing Data on Crop Classification Accuracy. *International Journal of Geoinformation*, 8(502).
- Thakur, P. and Jaswal, S., Mapping urban stress and green depletion in Shimla using remote sensing: A step towards sustainable urban future.
- Uduporuwa, R.J.M., 2025. STATUS OF URBANIZATION IN SRI LANKA: A COMPREHENSIVE REVIEW OF LITERATURE.
- Ullah, W., Ahmad, K., Ullah, S., Tahir, A.A., Javed, M.F., Nazir, A., Abbasi, A.M., Aziz, M. and Mohamed, A., 2023. Analysis of the relationship among land surface temperature (LST), land use land cover (LULC), and normalized difference vegetation index (NDVI) with topographic elements in the lower Himalayan region. *Heliyon*, 9(2).
- United States Environmental Protection Agency (US EPA). (2016). Using trees and vegetation to reduce heat islands. <https://19january2017snapshot.epa.gov/heat-islands/using-trees-and-vegetation-reduce-heat-islands>

- urban planning in North Halmahera Regency. *KLIK: Kajian Ilmiah Informatika dan Komputer*, 4(2), 913–925. <https://doi.org/10.31227/osf.io/gdxep> (Add actual DOI if available)
- Viana, C. M., Oliveira, S., Oliveira, S. C., & Rocha, J. (2019). *Land Use/Land Cover Change Detection and Urban Sprawl Analysis Spatial Modeling in GIS and R for Earth and Environmental Sciences*.
- Weng, Q. (2012). Remote sensing of urban environments. In Q. Weng (Ed.), *Remote Sensing of Urban and Suburban Areas* (pp. 1–19). Springer. <https://doi.org/10.1007/978-1-4020-4385-7>
- Yasin, M. Y., Yusoff, M. M., & Noor, N. M. (2021). Urban sprawl literature review: Definition and driving force. *AGeografia Malaysian Journal of society and Space*, 17(2).
- Yasin, M.Y., Abdullah, J., Noor, N.M., Yusoff, M.M. and Noor, N.M., 2022, October. Landsat observation of urban growth and land use change using NDVI and NDBI analysis. In *IOP Conference Series: Earth and Environmental Science* (Vol. 1067, No. 1, p. 012037). IOP Publishing.



ICRES26_061

A GLOBAL REVIEW ON BIO-BASED SUPPLEMENTARY CEMENTITIOUS MATERIALS (SCMs) FOR SUSTAINABLE AND RESOURCE EFFICIENT CONCRETE

T.T.N. De Silva* , L.D.I.P. Seneviratne

University of Moratuwa, Bandaranayake Mawatha, Katubedda, Moratuwa, Sri Lanka.

**Correspondence E-mail: desilvatn.21@uom.lk, TP: +94783002677*

Abstract: This study employs a Narrative Literature Review to identify characteristics, applications, chemical composition, global abundance, sustainability, benefits and limitations of Bio-based SCMs. Being a significant contributor of global GHG emission, cement production is solely responsible for about 8% of the total emissions. The annual global cement demand which is about 4Gt, is expected to rise further due to urbanization and population trends. While industrial by-products as fly ash and Ground Granulated Blast Furnace Slag (GGBS) have been reducing the clinker content, the transition towards clean energy is precipitating a global scarcity of these materials as carbon-intensive industrial processes in coal-fired plants and primary steel furnaces are gradually being decommissioned. In contrast, waste-derived bio-based materials offer a resource-efficient pathway that valorizes agricultural and organic residues without total reliance on virgin raw materials or heavy industrial processes. This study focuses on the strategic shift towards bio-based Supplementary Cementitious Materials (SCMs) including Rice Husk Ash (RHA), Sugarcane Bagasse Ash (SCBA), Rice Husk Biochar (RHB), Nano Eggshell Powder (NEP) and Palm Oil Fuel Ash (POFA) as futuristic alternatives. Studies have revealed 2Gt of annual agricultural residues provide an abundant and regenerative resource base. Given the inherent challenges in achieving high structural strength without conventional cement, the review emphasizes application-driven adoption where performance requirements are moderate and significant environmental gains are guaranteed. Life Cycle Assessments confirm that top-performing bio-based SCMs can reduce the Global Warming Potential (GWP) of cement production by 50% to 90%. The findings highlight that while supply chain limitations and variability in material composition remain key challenges, bio-based materials demonstrate strong potential in resource-efficient concrete systems when matched appropriately with suitable applications. In conclusion, bio-based SCMs offer a resilient, resource efficient and sustainable pathway that mitigates the potential scarcity of industrial by-products in addition to their guaranteed reduction in carbon emissions.

Keywords: Bio-based Materials; Global Warming Potential; Partial Cement Replacements; Resource Efficiency; Supplementary Cementitious Materials; Sustainability

1. Introduction

Being one of the largest industrial contributors to global warming and climate change, construction industry is responsible for approximately 39% of the global CO₂ emission and 36% of global energy consumption (Chen et al., 2023). The cement production generally accounts for about 7-8% of the total global CO₂ emission confirming its significant environmental impact compared to any other individual building material (Olsson et al., 2023; Yang et al., 2024). The current global demand for cement is about 4 Gt per year and is expected to rise further due to urbanization and population trends (Shah et al., 2022). Using Industrial By-Products (IBPs) such as fly ash, Ground Granulated Blast Furnace Slag (GGBS), and silica fume as Supplementary Cementitious Materials (SCMs) is a strategy which had been proposed and implemented with the aim of reducing the significant GHG emission of concrete production. Siddiq et al. (2025) and Tran et al. (2025) report that replacing 30-50% of cement with IBPs has the potential to reduce the Global Warming Potential (GWP) of concrete by 25-61% compared to conventional material mixes.

But, with the global transition towards clean energy production and decarbonization, abandonment of coal energy plants has started, resulting a substantial reduction of the availability of coal fly ash in the future (Fořt et al., 2020; Olatoyan et al., 2023). Akintayo et al. (2025) highlight that availability of GGBS can be constrained due to the reduction in slag output followed by steel industry's transition from blast furnaces towards electric arc furnaces. Shah et al. (2022) have reported that the availability of conventional secondary cementitious materials such as coal fly ash and GGBS produced from Industrial By-Products (IBPs), has been declining compared to the cement production for the past 16 years. Refer Figure 1. Shah et al. (2022) have further reported that the global cement production has more than doubled from 1.80 Gt in 2002 to 4.05 Gt in 2018 mainly due to the socio-economic development in China (Cement production in China increased from 0.64 Gt in 2002 to 2.2 Gt in 2018). Since this rate of increase has occurred faster than the growth in total generation of secondary cementitious materials, the ratio of secondary cementitious materials to cement fell from 97% by mass (1.74 Gt) to 86% by mass (3.48 Gt). This decline could be mainly attributed to the reduced generation of coal fly ash and GGBS, two of the most used secondary cementitious materials, whose contribution changed from 25% (0.44 Gt) to 17% (0.70 Gt) by mass compared to the total cement production.

Ngayakamo and Onwualu (2022) attest that the global agricultural waste production each year including eggshells and rice husks is estimated to reach approximately 2 billion tons. Thomas et al. (2021) and Yin et al. (2025) suggest that valorising agricultural or biomass waste in cementitious composites can simultaneously tackle waste management, resource depletion, and CO₂ reduction, aligning with circular-economy and SDG targets. The aim of this study is to review global applications in bio-based materials used as partial replacements for cement, including their composition, production methods, environmental benefits and limitations associated.

2. Methodology

This global study on Bio-based Materials has adopted a Narrative Literature Review (NLR) due to the broad and heterogeneous nature of their applications, benefits and limitations in the global context. Narrative reviews are more appropriate when the objective is to provide an integrative overview, identify themes and gaps, and synthesize diverse evidence rather than answering a narrow pre-defined question (Ahmad, 2025). Published literature (journal articles, conference papers, books, reports) after 2020 (including 2020) were selected based on their titles and keywords. Selection bias may have arisen because the review is not systematic and relies on studies identified solely through database searches and author judgement. To reduce this risk, multiple databases as Scopus, Google Scholar were searched using broad combinations of the keywords 'bio-based', 'supplementary cementitious materials', 'cement replacement', 'agricultural waste', 'ash', 'biochar' and 'low-carbon'. Reference lists of key papers were also screened (snowballed) to identify additional relevant studies. Though a formal tool to reduce the bias risk was not applied, studies were appraised informally for relevance and quality. Priority was given to peer-reviewed journal articles reporting experimental or quasi-experimental work specifically on applications of bio-based SCMs in concrete. Only the articles published in English were

included, relevant work published in other languages have not been considered, resulting language bias as another limitation.

3. Findings and Analysis

3.1 Transition from conventional SCMs to Bio-based SCMs

According to Akintayo et al. (2023) and Caldas et al. (2022), substitution of cement and aggregates with low carbon alternatives is the most effective strategy to reduce carbon emissions, having proved that a reduction of 94% is possible depending on the level of substitution and the material used. The use of mineral based Industrial By-Products (IBP) such as fly ash, Ground Granulated Blast Furnace Slag (GGBS) and silica fume as Supplementary Cementitious Materials (SCMs) is a method which had been frequently proposed and implemented to reduce the GHG emissions of concrete production. Replacing 30-50% of cement with IBPs has the potential to reduce the Global Warming Potential (GWP) of concrete by 25-61% compared to conventional material mixes (Khankhaje et al., 2024; Qaidi et al., 2022; Siddiq et al., 2025; Tran et al., 2025).

Figure 1 below depicts the global generation rates of secondary CMs from 2002 to 2018. Maximal substitution of Portland cement clinker with these materials could have avoided up to 1.3 Gt of CO₂-equivalent (~44% of cement production and ~2.8% of anthropogenic emissions of CO₂-equivalent) in 2018. It also shows that almost all the highest cement producing countries can locally generate and use secondary CMs substituting by up to 50% of their domestic Portland cement clinker, while majority of the countries are able to potentially substitute 100% of their Portland cement clinker. This figure thereby highlights the importance of following regionally optimized mix designs for CMs and systemic decarbonizing approaches to the global CMs cycle (Shah et al., 2022).

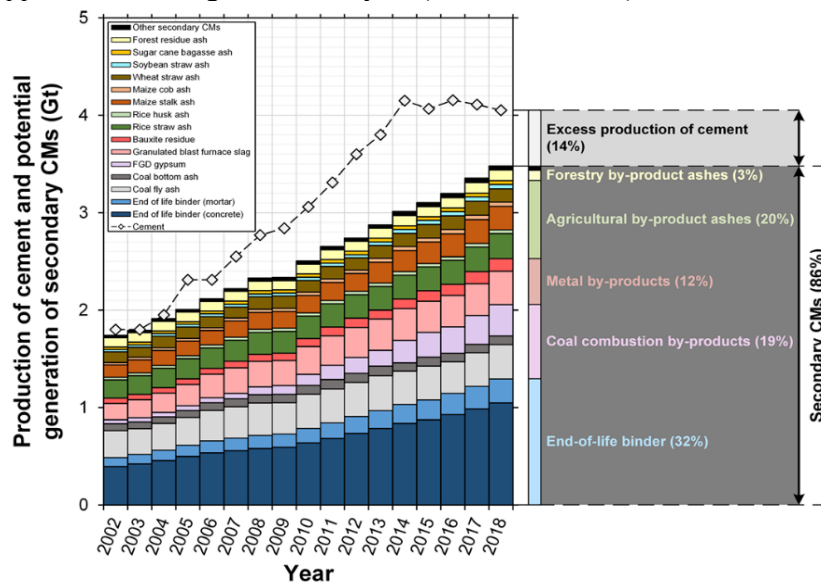


Figure 1: Global Production of Cement and Generation of Secondary Cementitious Materials (Shah et al., 2022)

Ngayakamo and Onwualu (2022) attest that the global agricultural waste production including eggshells and rice husks is estimated to reach approximately 2 Gt per year. Since the cement production keeps increasing and the abundance of IBPs also may decrease, focusing more on bio-based SCMs stands as a futuristic and sustainable option in the current context.

Reported CO₂ emissions for producing agricultural ashes such as RHA and SCBA are on the order of 26-103 kg CO₂ per tonne, far below that of cement (800-1000 kg CO₂ per tonne). When such ashes are used to replace clinker, the incremental emissions resulted from collection and processing of them are minor compared to the major avoided emissions, landfill and open dumping from cement production. Therefore, agricultural SCMs can reduce the carbon emissions and promote sustainable

construction by lowering the reliance on clinker production (Onsongo et al., 2025). Onsongo et al. (2025) further highlight that despite this transition from a clinker-dependent production to a bio-based process giving rise to challenges in addition to its opportunities, it has now become a critical strategic decision to make in reducing carbon emissions and improving sustainability in the current context.

3.2 Advantages of Bio-based Materials as Supplementary Cementitious Materials (SCMs)

Majority of the conventional SCMs are inorganic (mineral based) materials with the potential to reduce CO₂ emissions by reducing the cement clinker content (Gupta et al. 2020; Senadheera et al. 2023). Conventional SCMs produced by Industrial By-Products (IBP) such as Fly Ash (FA), GGBS, and Silica Fume (SF) are commonly being used in the global cement and concrete industry due to their specific pozzolanic activities and mechanical properties (Fořt et al. 2024; Shakouri et al. 2020; Suarez-Riera et al. 2020).

3.2.1 Reduction of the Carbon Emission resulted from Clinker production

Clinker production accounts for approximately 93.9% from the total Global Warming Potential (GWP) of traditional cement production. The GWP of clinker is significant due to the calcination of limestone and combustion of fuel during clinkerization, resulting 897 kg CO₂-equivalent per ton of clinker produced (Petroche & Ramirez, 2022). Therefore, reducing the clinker content in cement with the use of SCMs or alternative binders can lower emissions by 25-70%, depending on the approach utilized (Nie et al., 2022; Supriya et al. 2023). Durastanti and Moretti (2024) state that it is critical to reduce the production of clinker in order to achieve climate targets by reducing the environmental impact from the construction sector.

Onsongo et al. (2025) emphasise that incorporation of agricultural-based SCMs such as Rice Husk Ash (RHA), coffee husk ash, Sugarcane Bagasse Ash (SCBA) and Palm Oil Fuel Ash (POFA) into cement production can result in a significant reduction of the clinker requirement, while maintaining the performance standards of Ordinary Portland Cement (OPC). Onsongo et al. (2025) further attest that locally sourced waste materials can lower the carbon footprint of cement by up to 40%, presenting itself as a promising solution to lower the clinker content.

3.2.2 Reduction of Waste Disposal burden through Re-utilization

Duque-Acevedo et al. (2022) highlight that reframing of agricultural waste biomass such as rice husk, sugarcane bagasse and other residues from a disposal problem towards a secondary raw material for concrete, bricks and other building products, helps to close loops between agriculture and construction.

While SCMs such as fly ash, GGBS and silica fume are sourced from industrial by-products, exhibiting a smart method for waste utilization, sustainability and long-term availability of them are now under scrutiny mostly due to the impending shutdown of coal-fired power plants (due to the global transition towards clean energy sources), challenging the consistent supply of fly ash in the future (Ahmed et al., 2024). Akintayo et al. (2025) also warned that availability of GGBS may get constrained due to the reduction in slag output resulted by steel industry's transition from blast furnaces towards electric arc furnaces. Onsongo et al. (2025) report that incorporating agricultural ashes as SCMs in Africa, has the potential to reduce the carbon footprint of cement by up to 40% through lowering clinker demand and avoiding waste disposal emissions.

3.2.3 Enhancing Durability Properties of Concrete

Ashes which are rich in silica such as RHA, SCBA react with Ca(OH)₂ and form additional calcium silicate hydrate (C-S-H), to give better strength and durability (Adhikary et al., 2022; Ahmed, 2024). RHA, SCBA and SCFA refine the pore structure, reduce permeability, water absorption, chloride ingress, and improve the resistance to acids and sulphates at optimum contents, ultimately increasing the durability properties of concrete (Adhikary, Ashish & Rudžionis, 2022). Neto et al., 2021) found that 5% replacement of SCBA has resulted 97% increase in service life against chloride ingress and mitigation of Alkali Silica Reaction (ASR) by forming additional C-S-H. In depth reviews on SCMs

have quantified that 5-20% of SCM replacement can increase the long-term durability by 15-30% while lowering the CO₂ emissions (Fode et al., 2023).

3.2.4 Carbon Sequestration Potential

Carbon sequestration is capturing CO₂ from the atmosphere and storing its carbon in a form that stays out of the air for longer periods as decades to centuries or more. All substances with a long lifecycle including but not limited to soil, vegetation, oceans, rocks and can act as carbon reservoirs (Don et al., 2024; Osman et al., 2022). Usually bio-based materials such as straw, wood, paper, food waste, bamboo are not sequestering Carbon. This occurs because these materials ultimately decompose, after which microorganisms convert their stored carbon back into CO₂ (or CH₄), thereby completing the short-term carbon cycle rather than enabling long-term carbon sequestration. Unlike usual bio-based materials, biochar is a carbon-rich solid produced by pyrolyzing biomass under oxygen-limited conditions, resulting in a highly stable, aromatic carbon structure that can persist in soil for decades to centuries (Luo et al., 2023). This microstructural stability allows biochar such as coffee or rice husk biochar to act as a carbon sink by physically protecting carbon from microbial decomposition and chemically binding with soil minerals, sequestering carbon in the soil and reducing atmospheric CO₂ levels (Li & Tasnady, 2023). Don et al. (2024) and Fawzy et al. (2021) argue carbon sequestration to be beneficial because it creates negative emissions, helping offset fossil CO₂ which is hard to eliminate and ultimately contributing to mitigation of climate change.

3.2.5 Resource Efficiency & Reduction in Primary Extraction

The partial substitution of non-renewable raw materials such as limestone, clay and other virgin materials required for cement production with bio-based SCMs, reduces the need for conventional SCMs (often industrial by-products). Long-term availability of SCMs such as fly ash, GGBS and silica fume which are produced from Industrial By-Products is rendered uncertain in the current context (Charitha et al., 2021; Thomas et al., 2021).

Ashes from waste such as rice husk and sugarcane bagasse are prevalent in tropical and subtropical regions, while barley, canola and oats are cold weather crops that demonstrate promising pozzolanic activity (Ahmed et al., 2024). Ability to obtain agricultural ashes from diverse climates improves the resilience of supply chains and provides a geographically wide resource base for low-carbon concrete.

3.2.6 Circularity and Sustainability

The sustainability of biomass ashes depends significantly on their sourcing pathway. If these Bio-based materials are generated as unavoidable by-products of existing energy production or agricultural processes (biomass power plants, chena cultivation), their use as SCMs can significantly reduce net CO₂ emissions by minimizing the existing clinker production (Ahmed et al., 2024).

This transition towards Bio-Based Materials as SCMs not only decreases the carbon emissions resulting from cement production but also supports sustainable construction through achieving global climate targets and SDGs such as Responsible Consumption and Production (SDG 12) and Climate Action (SDG 13) (Onsongo et al., 2025). Onsongo et al. (2025) further highlight that adopting green cement could revolutionize the cement industry by improving resource efficiency and promoting sustainable development across the globe. Valorising AWB reduces landfilling, open burning, and associated air and land pollution. It is explicitly being promoted under EU Circular Economy Plan and bioeconomy policies. Since policy frameworks and strategies becoming increasingly centred on replacing fossil-based and mineral raw materials with bio-based, renewable, and recycled feedstocks in the construction value chain (Le, Salomone & Nguyen, 2023), this transition towards Bio-based SCMs stands as a futuristic and sustainable solution in the current context.

3.3 Characteristics of Commonly utilized Bio-based Materials as SCMs in the Global Context

3.3.1 Rice Husk Ash (RHA)

Rice Husk Ash is obtained through combustion of the protective covering of rice grains which is an agricultural waste material. Following a controlled incineration or burning of rice husks, it undergoes a grinding process to achieve high fineness. The temperature is controlled around 600-800°C to maximize the reactivity by producing more amorphous silica rather than obtaining more crystalline silica (Khankhaje et al., 2025; Suomie, Mishra & Das, 2025). Production of RHA incurs less than 10% of the GHG emissions associated with the total clinker production, transforming a voluminous agricultural waste which is often dumped or openly burned, into a valuable resource (Montazeri et al., 2025). Khankhaje et al. (2025) further highlight that utilization of RHA will reduce the demand for limestone extraction and energy-intensive cement manufacturing.

Its high content of amorphous silica (85-95%) and large specific surface area makes it highly pozzolanic. Calcium silicate hydrate (C-S-H) gel formed by the reaction of RHA with calcium hydroxide refines the pore structure, increases compressive strength (optimal at 10-20% replacement), and reduces the chloride permeability by a significant amount (Montazeri et al., 2025; Suomie, Mishra & Das, 2025). But, the porous and hygroscopic nature of RHA particles increase the water demand of the mix and can reduce concrete's workability if superplasticizers are not used (Khankhaje et al., 2025; Suomie et al., 2025).

3.3.2 Rice Husk Biochar (RHB)

A carbon-rich, porous material produced from the thermochemical conversion (via pyrolysis) of rice husk waste, distinct from Rice Husk Ash (RHA) due to its high fixed carbon content and lower silica levels. Pyrolysis helps to retain more fixed carbon compared to ash since the thermal decomposition takes place in an oxygen-limited environment unlike full combustion (Chen et al., 2025). RHB has the ability to act as a carbon sink, sequestering carbon within the concrete matrix. Studies show that it can decrease the GWP of traditional cement by up to 88%, as it offers a negative emission potential (T. Chen et al., 2025).

Its honeycomb shaped porous structure helps to sustain hydration, creating a reservoir effect for internal curing by gradually releasing water and mitigating autogenous shrinkage while enhancing long-term strength combustion (Chen et al., 2025; Senadheera et al., 2023). Chen et al. (2025) further state that RHB contains lower levels of impurities compared to RHA and can accelerate the setting time by acting as nucleation sites promoting the formation of hydration products and densifying the matrix. Since the silica content is lower than in RHA, its primary role is often as a filler and internal curing agent rather than a highly reactive pozzolan. Excessive dosages of RHA have the potential to compromise the structural integrity due to high porosity (Chen et al., 2025; Senadheera et al., 2023).

3.3.3 Sugarcane Bagasse Ash (SCBA) / Fly Ash (SCFA)

SCBA obtained from the boiler exhaust (fly ash) or bottom ash of sugar mills after burning the bagasse (the fibrous residue of sugarcane) for energy generation purposes can also be identified as a significantly resource efficient material (Abbass & Akhai, 2025; Alvarenga & Cordeiro, 2024). Abbass and Akhai (2025) further attest that it is a valorization of an energy generation by-product which will otherwise be dumped somewhere, while preventing potential land and groundwater contamination. To be used as a cement replacement, SCBA obtained from sugar industry boilers often requires minimal processing as drying, sieving or grinding to reduce particle size and increase reactivity (Abbass & Akhai, 2025; Yaseen, 2024). They further state that the high energy costs associated with intensive industrial grinding can also be avoided by using SCBA which has been minimally processed.

SCBA has pozzolanic ability since it contains silica and alumina to react with calcium hydroxide forming binding gels (C-S-H). It can also improve the long-term compressive strength up to 8% over reference mortars and has the potential to enhance the acid resistance (Abbass & Akhai, 2025; Alvarenga & Cordeiro, 2024). However, Alvarenga and Cordeiro (2024) have identified that SCBA can reduce the workability due to its increased water absorption and capillarity which can be attributable to

irregular, fibrous and honeycomb shapes of the SCBA particles. Moreover, depending on the source of collection of SCBA, Quartz and carbon particles can also be present as contaminants.

3.3.4 Nano Eggshell Powder (NEP)

NEP is a calcium-rich bio filler and cementitious additive derived from poultry waste, specifically processed to the nanoscale to enhance the properties of High-Strength Concrete (HSC). Nanoparticles obtained through washed, dried and calcined (sometimes) eggshells through extended grinding or by other specific synthesis methods can be used as a bio-filler or accelerator (Amin et al., 2022).

Amin et al. (2022) further highlight its diversion of food waste from landfills and reduces the consumption of natural limestone (calcium carbonate) resources. Since NEP can accelerate the setting time of concrete while improving its microstructure by filling pores in contrast to most of the other pozzolans, it can be used in combination with waste derived pozzolans like SCBA, to compensate for the delay in setting time caused by the ash (Amin et al., 2022).

3.3.5 Palm Oil Fuel Ash (POFA)

POFA is a by-product generated by the palm oil production which is the highest-produced vegetable oil globally. It is a black powder produced when oil palm shells, empty fruit bunches and fibers are burned in power plant boilers at temperatures 850°C-1000°C to generate electricity and heat for the mills (Ahmed et al., 2024). Globally, the palm oil industry produces over 60 million tons of oil per year, generating approximately 12 Mt of POFA as waste. Malaysia and Indonesia jointly account for nearly 80% of this output (Ahmed et al., 2024). It has been further highlighted that, due to its low nutritional value, POFA is usually discarded in open fields where it can get carried by the wind leading to smog, visibility issues and severe respiratory health hazards. Repurposing POFA as an SCM solves a significant waste disposal issue in addition to the guaranteed reduction in carbon footprint and energy consumption of cement production. Depending on the varying combustion efficiency of the power plant, POFA can contain high levels of unburned carbon with high LOI values (up to 21.6%), which can negatively interfere with the cement matrix. POFA possesses excellent pozzolanic reactivity and can increase the ultimate strength and durability of concrete (Oyejobi et al., 2024). It can significantly lower the chloride penetrability of concrete and massively improves its resistance to sulfate attacks and Alkali-silica reactions (ASR). POFA can it can significantly prolong both initial and final setting times while higher replacement levels can cause up to a 50% reduction in slump, requiring superplasticizers to maintain the workability (Ahmed et al., 2024).

3.4 Global Applications of Bio-based Materials as SCMs in concrete

Below, Table 1: Global Applications of Bio-based Materials as SCMs, summarises the applications of different bio-based materials in the global context. The application of RHA and Biochar marked as “potential” in the table are recommendations given by the author, unlike all other actual applications which are reported here.

Table 1: Global Applications of Bio-based Materials as SCMs

Bio-based SCM	Applications	Sources
Rice Husk Ash (RHA)	Concrete pavement for a NT2 (medium traffic) road in Columbia, replacing cement 24.9% of RHA	A
	In blended cements to improve durability and sustainability	B, C
	As a pozzolanic additive in blocks and masonry units	D
	For Pervious / porous concretes for stormwater management (<i>potential</i>)	E
Sugarcane Bagasse Ash (SCBA)	In Reinforced Concrete (RC) beams known as SCBA-RPET beams	F
	In High-Strength Concrete (HSC) properties with Nano Eggshell Powder (NEP)	G
	In blended cements with RHA or other SCMs to enhance durability	D

	As a filler in Two-Stage Concrete (TSC), Ultra High-Performance Concrete (UHPC) and Self-Compacting Concrete (SCC)	H
RHA & SCBA	Eco-friendly geopolymers bricks from alkali-activated SCBA and RHA	I
	In pavement-oriented concretes replacing 10-20% of cement while improving mechanical and durability performance	N
Biochar (in general)	In precast concrete elements as blocks, panels and pavers to enhance sustainability	J, K
	Agricultural waste-derived biochar (RHA, SCBA) in manufacturing concrete, bricks, and reinforced panels	J
	As an additive in asphalt mixtures for road construction due to its binding properties and potential to improve durability (<i>potential</i>)	L
Palm Oil Fuel Ash (POFA)	For ordinary, aerated and Ultra High Strength reinforced concrete in Malaysia	O, P
	For Self-Compacting Concrete (SCC) in Thailand and Malaysia at a 30-40% replacement	Q
	15-25% POFA is appropriate for reinforced concrete - A study in Bangladesh (<i>potential</i>)	Q

A - (Camargo-Pérez, Abellán-García & Fuentes, 2023), B - (Ozturk et al., 2022), C - (Hu, He & Zhang, 2020), D - (Jittin, Bahurudeen & Ajinkya, 2020), E - (Khankhaje et al., 2025a), F - (Daniel, Onchiri & Omondi, 2024), G - (Amin et al., 2022), H - (Abdalla et al., 2024), I - (Abbass & Akhai, 2025), J - (Duque-Acevedo et al., 2022), K - (Legan, Gotvajn & Zupan, 2022), L - (Kumar et al., 2023), M - (Infurna, Caruso & Dintcheva, 2023), N - (Narayanan & Kumar, 2025), O - (Amran et al., 2021), P - (Olivia et al., 2024), Q - (Mujedu et al., 2020)

Khan et al. (2025) establish that substitution of 10% of OPC with unprocessed RHA provides an eco-friendly and cost-efficient pathway towards green construction in Bangladesh and other rice-producing regions. As a significant structural application, SCBA used as a 5% partial cement substitute in Reinforced Concrete (RC) beams (SCBA-RPET beams) has shown to be suitable for use because of their concrete shear strain pattern (Daniel, Onchiri & Omondi, 2024). Amran et al. (2021) and Olivia et al. (2024) note that in Malaysia, properly processed POFA had been used as an SCM in concrete since the 1990s, showing successful performance in ordinary, aerated and ultra-high-strength reinforced concretes. In Thailand and Malaysia, Self-Compacting Concrete (SCC) with POFA has been developed extensively, with up to 30-40% cement replacement while meeting the required flow for SCC and providing medium to higher strength suitable for structural and precast SCC elements (Mujedu et al., 2020). A structural-grade concrete study from Bangladesh has used samples up to 45% POFA as cement replacement and showed optimum mechanical performance at 15-25% POFA, achieving ~39 MPa at 28 days (appropriate for reinforced concrete elements) (Mujedu et al., 2020).

3.5 Limitations for the use of Bio-based Materials as SCMs in concrete

The use of agricultural ashes as sustainable SCMs provides a strategic direction for the construction industry to adopt low-carbon concrete solutions across various climates while promoting advancements in production methods, performance standards, and emerging technologies such as hybrid materials and 3D printing (Ahmed et al., 2024). Onsongo et al. (2025) highlight that cost-efficient processing, policy support and market awareness are critical for scaling up the use of agricultural SCMs while variability in material quality, processing infrastructure and poor supply chains can be identified as limitations for large-scale adoption of them.

3.5.1 Reduced Workability of concrete due to high water demand

These waste derived SCMs often require grinding which leads to very fine particles. Due to the large surface area of these fine particles, the overall water demand increases (Jhatial et al., 2023). Upon 10-20% replacement of most of these ashes such as RHA, SCBA, slump may often decrease and require

more water or superplasticizer due to their porous and very fine microstructure (Charitha et al., 2021; Thomas et al., 2021).

3.5.2 Loss of Strength at Higher Dosages

When bio-based materials are used as partial cement replacements, the strength typically increases only up to an optimum level of dosage. After a broad review, Sakir et al. (2020) have concluded that 5-20% replacement by SCMs usually enhances strength and durability, but excessive replacement or overly reactive SCMs can disturb the $\text{Ca}(\text{OH})_2$ buffer and compromise the steel passivity and performance. During a study where several mixes of SCBA and RHA were used, most mixes having a replacement level of ~5-10% have reduced the compressive strength (Channa et al., 2022; Memon et al., 2022). Usually, agricultural ashes increase water absorption and reduce mix fluidity at higher levels, leading to a more porous microstructure and eventually a lower compressive strength (Ahmed, 2024).

3.5.3 Variability in the Material Composition

Composition of bio-based materials ashes (SiO_2 , CaO , unburnt carbon, alkalis) produced from agricultural and biomass ashes varies with the feedstock, season and combustion conditions, leading to changes in their oxide composition, carbon content and mineralogy to result in inconsistent reactivity and concrete performance (Bora et al., 2024; Park & Lee, 2024). Overmann et al. (2025) and Zhao et al. (2024) have warned that despite their own name as RHA, Wood Ash or Biochar, the feedstock and process conditions jointly control a bio-based material's carbon content, residual ash content, silica form (crystalline or amorphous), alkalis and trace elements, resulting their characteristics to range from a beneficial pozzolan to an essentially inert diluent or a performance-impairing additive. Since the material composition can vary with the soil type, water availability, temperature and soil fertility even for the same species, two samples of rice husk or straw from different farms or seasons can yield ashes and biochar with different oxide ratios and Loss on Ignition (LOI). Thomas et al. (2021) state that ashes which are poorly burned or inadequately (coarsely) ground are less reactive and can reduce strength and durability. Pozzolanic reactivity of SCBA has been tripled and improved the performance of concrete by sieving followed by grinding for 45 minutes.

3.5.4 Lack of Standards and Specifications

Adhikary, Ashish and Rudžionis (2022) and Endale et al. (2023) emphasize the high variability in ash composition (SiO_2 content, fineness, LOI test results) and lack of standard specifications compared to those of fly ash and GGBS, will constantly need case-by-case optimisations which will be inefficient and inconsistent. Ahmed et al. (2024) and Snellings et al. (2023) highlight that though coal fly ash has ASTM C618 to benchmark the standards, there are no dedicated and widely recognized standards for Bio-based SCMs, specially in North American and European regions.

3.5.5 Supply chain and Scalability Limitations

The potential of agricultural SCMs is often scarce relative to the national clinker demand. Amadi and Mahachi (2025) question their impact at scale by highlighting that agricultural waste SCMs in South Africa can only replace about 1.5% of its clinker demand. Arrigoni et al. (2020) have identified geographical dependence also as a retarder since agricultural residues are often being concentrated in specific regions and transporting them for long distances may nullify their economic and environmental benefits.

4. Conclusions and Recommendations

The transition towards bio-based SCMs as partial cement replacements offers a promising pathway to enhance sustainability through resource efficiency in cement production. The significant GHG emission and resource intensity of Portland cement manufacturing establish the need of integrating bio-based SCMs derived from agricultural residues. They provide a practical strategy to reduce clinker content in addition to the valorisation of industrial waste streams. These materials contribute to lower embodied carbon, reduced reliance on virgin raw materials, and improved circularity within the construction sector. Global applications demonstrate that bio-based SCMs can maintain or enhance long-term mechanical and durability performance, when properly processed and proportioned. However,

challenges such as variability in material properties, reduction in fresh concrete properties, limited standardization, and supply chain constraints continue to restrict their widespread adoption. Addressing these barriers through research, establishing quality control measures, and supportive regulatory frameworks will be critical in the future. In conclusion, the use of bio-based SCMs from an application-based approach is a viable and resource-efficient strategy towards sustainable concrete and broader decarbonisation efforts for the future of the built environment.

References

- Abbass, M., & Akhai, S. (2025). Eco-friendly geopolymers bricks synthesized from alkali-activated sugarcane bagasse ash and rice husk ash. *Industrial Crops and Products*, 233, 121410. <https://doi.org/10.1016/J.INDCROP.2025.121410>
- Abdalla, T. A., Hussein, A. A. E., Ahmed, Y. H., & Semmana, O. (2024). Strength, durability, and microstructure properties of concrete containing bagasse ash – A review of 15 years of perspectives, progress and future insights. *Results in Engineering*, 21. <https://doi.org/10.1016/j.rineng.2024.101764>
- Adhikary, S. K., Ashish, D. K., & Rudžionis, Ž. (2022). A review on sustainable use of agricultural straw and husk biomass ashes: Transitioning towards low carbon economy. *Science of the Total Environment*, 838. <https://doi.org/10.1016/j.scitotenv.2022.156407>
- Ahmad, M. N. (2025). Narrative Literature Reviews in Scientific Research: Pros and Cons. *Jordan Journal of Agricultural Sciences*, 21(1), 1–4. <https://doi.org/10.35516/jjas.v21i1.4143>
- Ahmed, A. (2024). Assessing the effects of supplementary cementitious materials on concrete properties: A review. *Discover Civil Engineering*, 1(1). <https://doi.org/10.1007/s44290-024-00154-z>
- Ahmed, M. M., Sadoon, A., Bassuoni, M. T., & Ghazy, A. (2024). Utilizing Agricultural Residues from Hot and Cold Climates as Sustainable SCMs for Low-Carbon Concrete. *Sustainability* 2024, Vol. 16, Page 10715, 16(23), 10715. <https://doi.org/10.3390/su162310715>
- Akintayo, B. D., Akintayo, D. C., & Olanrewaju, O. A. (2023). Material Substitution Strategies for Energy Reduction and Greenhouse Gas Emission in Cement Manufacturing. In *Atmosphere* (Vol. 14, Number 8). Multidisciplinary Digital Publishing Institute (MDPI). <https://doi.org/10.3390/atmos14081200>
- Akintayo, B. D., Babatunde, O. M., Akintayo, D. C., & Olanrewaju, O. A. (2025). Transforming Industrial Waste into Low-Carbon Cement: A Multi-Criteria Assessment of Supplementary Cementitious Materials for Sustainable Concrete Design. *Recycling*, 10(6), 211. <https://doi.org/10.3390/recycling10060211>
- Alvarenga, K. P., & Cordeiro, G. C. (2024). Evaluating sugarcane bagasse fly ash as a sustainable cement replacement for enhanced performance. *Cleaner Engineering and Technology*, 20, 100751. <https://doi.org/10.1016/J.CLET.2024.100751>
- Amadi, I. G., & Mahachi, J. (2025). Towards Sustainable Concrete: Current Trends and Future Projections of Supplementary Cementitious Materials in South Africa. *Construction Materials*, 5(3). <https://doi.org/10.3390/constrmater5030070>
- Amin, M., Attia, M. M., Agwa, I. S., Elsakhawy, Y., el-hassan, K. A., & Abdelsalam, B. A. (2022). Effects of sugarcane bagasse ash and nano eggshell powder on high-strength concrete properties. *Case Studies in Construction Materials*, 17, e01528. <https://doi.org/10.1016/J.CSCM.2022.E01528>
- Amran, M., Lee, Y. H., Fediuk, R., Murali, G., Mosaberpanah, M. A., Ozbakkaloglu, T., Lee, Y. Y., Vatin, N., Klyuev, S., & Karelia, M. (2021). Palm oil fuel ash-based eco-friendly concrete composite: A critical review of the long-term properties. *Materials*, 14(22). <https://doi.org/10.3390/ma14227074>
- Neto, J. da S. A., de França, M. J. S., Amorim Júnior, N. S. de, & Ribeiro, D. V. (2021). Effects of adding sugarcane bagasse ash on the properties and durability of concrete. *Construction and Building Materials*, 266. <https://doi.org/10.1016/j.conbuildmat.2020.120959>
- Aneja, A., Sharma, R. L., & Singh, H. (2022). Mechanical and durability properties of biochar concrete. *Materials Today: Proceedings*, 65, 3724–3730. <https://doi.org/10.1016/J.MATPR.2022.06.371>
- Arrigoni, A., Panesar, D. K., Duhamel, M., Opher, T., Saxe, S., Posen, I. D., & MacLean, H. L. (2020). Life cycle greenhouse gas emissions of concrete containing supplementary cementitious materials: cut-off vs. substitution. *Journal of Cleaner Production*, 263. <https://doi.org/10.1016/j.jclepro.2020.121465>
- Bora, N., Daimary, N., Athparia, M., Loganathan, M. K., & Katakai, R. (2024). Optimization of biogenic supplementary cementitious materials in concrete prepared from East-Indian Lemon Grass (*Cymbopogon flexuosus*) and poultry litter using response surface methodology. *Energy, Ecology and Environment*, 9(4), 382–403. <https://doi.org/10.1007/s40974-024-00320-0>

- Caldas, L. R., de Araujo, A. F., Hasparyk, N. P., Tiecher, F., Amantino, G., & Filho, R. D. T. (2022). Circular economy in concrete production: Greenhouse Gas (GHG) emissions assessment of rice husk bio-concretes. *Revista IBRACON de Estruturas e Materiais*, 15(6). <https://doi.org/10.1590/S1983-41952022000600002>
- Camargo-Pérez, N. R., Abellán-García, J., & Fuentes, L. (2023). Use of rice husk ash as a supplementary cementitious material in concrete mix for road pavements. *Journal of Materials Research and Technology*, 25, 6167–6182. <https://doi.org/10.1016/J.JMRT.2023.07.033>
- Channa, S. H., Mangi, S. A., Bheel, N., Soomro, F. A., & Khahro, S. H. (2022). Short-term analysis on the combined use of sugarcane bagasse ash and rice husk ash as supplementary cementitious material in concrete production. *Environmental Science and Pollution Research*, 29(3), 3555–3564. <https://doi.org/10.1007/s11356-021-15877-0>
- Charitha, V., Athira, V. S., Jittin, V., Bahurudeen, A., & Nanthagopalan, P. (2021). Use of different agro-waste ashes in concrete for effective upcycling of locally available resources. *Construction and Building Materials*, 285. <https://doi.org/10.1016/j.conbuildmat.2021.122851>
- Chen, L., Huang, L., Hua, J., Chen, Z., Wei, L., Osman, A. I., Fawzy, S., Rooney, D. W., Dong, L., & Yap, P. S. (2023). Green construction for low-carbon cities: a review. *Environmental Chemistry Letters*, 21(3), 1627–1657. <https://doi.org/10.1007/s10311-022-01544-4>
- Chen, T., Yang, Z., Liu, H., Li, L., Qin, L., & Gao, X. (2025). Effect of biochar characteristics on freeze-thaw durability of biochar-cement composites. *Journal of Building Engineering*, 102, 111959. <https://doi.org/10.1016/J.JOBE.2025.111959>
- Daniel, C., Onchiri, R. O., & Omondi, B. O. (2024). Structural behaviour of reinforced concrete beams containing recycled polyethylene terephthalate and sugarcane bagasse ash. *Applications in Engineering Science*, 18, 100178. <https://doi.org/10.1016/J.APPLES.2024.100178>
- Don, A., Seidel, F., Leifeld, J., Kätterer, T., Martin, M., Pellerin, S., Emde, D., Seitz, D., & Chenu, C. (2024). Carbon sequestration in soils and climate change mitigation—Definitions and pitfalls. *Global Change Biology*, 30(1). <https://doi.org/10.1111/gcb.16983>
- Duque-Acevedo, M., Lancellotti, I., Andreola, F., Barbieri, L., Belmonte-Ureña, L. J., & Camacho-Ferre, F. (2022). Management of agricultural waste biomass as raw material for the construction sector: an analysis of sustainable and circular alternatives. *Environmental Sciences Europe*, 34(1). <https://doi.org/10.1186/s12302-022-00655-7>
- Durastanti, C., & Moretti, L. (2024). Assessing the climate effects of clinker production: A statistical analysis to reduce its environmental impacts. *Cleaner Environmental Systems*, 14. <https://doi.org/10.1016/j.cesys.2024.100204>
- Endale, S. A., Taffese, W. Z., Vo, D. H., & Yehualaw, M. D. (2023). Rice Husk Ash in Concrete. *Sustainability (Switzerland)*, 15(1). <https://doi.org/10.3390/su15010137>
- Fawzy, S., Osman, A. I., Yang, H., Doran, J., & Rooney, D. W. (2021). Industrial biochar systems for atmospheric carbon removal: a review. *Environmental Chemistry Letters*, 19(4), 3023–3055. <https://doi.org/10.1007/s10311-021-01210-1>
- Fode, T. A., Chande Jande, Y. A., & Kivevele, T. (2023). Effects of different supplementary cementitious materials on durability and mechanical properties of cement composite – Comprehensive review. *Heliyon*, 9(7). <https://doi.org/10.1016/j.heliyon.2023.e17924>
- Fořt, J., Šál, J., Keppert, M., Mildner, M., Hotěk, P., Ślosarczyk, A., Klapiszewski, Ł., & Černý, R. (2024). Durability analysis of sustainable mortars with biomass fly ash as high-volume replacement of Portland cement. *Journal of Building Engineering*, 91, 109565. <https://doi.org/10.1016/J.JOBE.2024.109565>
- Fořt, J., Šál, J., Žák, J., & Černý, R. (2020). Assessment of wood-based fly ash as alternative cement replacement. *Sustainability (Switzerland)*, 12(22), 1–16. <https://doi.org/10.3390/su12229580>
- Gupta, S., Krishnan, P., Kashani, A., & Kua, H. W. (2020). Application of biochar from coconut and wood waste to reduce shrinkage and improve physical properties of silica fume-cement mortar. *Construction and Building Materials*, 262, 120688. <https://doi.org/10.1016/J.CONBUILDMAT.2020.120688>
- Hu, L., He, Z., & Zhang, S. (2020). Sustainable use of rice husk ash in cement-based materials: Environmental evaluation and performance improvement. *Journal of Cleaner Production*, 264. <https://doi.org/10.1016/j.jclepro.2020.121744>

- Infurna, G., Caruso, G., & Dintcheva, N. T. (2023). Sustainable Materials Containing Biochar Particles: A Review. *Polymers*, 15(2). <https://doi.org/10.3390/polym15020343>
- Jhatal, A. A., Nováková, I., & Gjerløw, E. (2023). A Review on Emerging Cementitious Materials, Reactivity Evaluation and Treatment Methods. *Buildings*, 13(2). <https://doi.org/10.3390/buildings13020526>
- Jittin, V., Bahurudeen, A., & Ajinkya, S. D. (2020). Utilisation of rice husk ash for cleaner production of different construction products. *Journal of Cleaner Production*, 263. <https://doi.org/10.1016/j.jclepro.2020.121578>
- Khan, M. Z. H., Rokonzaman, M., Shajahan Ali, M., Alam, M. M., Tayef, M. M. H., Nabi, S. M. N., & Muhammad, S. (2025). Exploring Rice Husk Ash in Uncontrolled Condition as Supplementary Cementitious Materials for Enhanced Performance in Construction Materials. *Academic International Journal of Engineering Science*, 3(02), 01–11. <https://doi.org/10.59675/e321>
- Khankhaje, E., Jang, H., Kim, J., & Rafieizonooz, M. (2025a). Utilizing rice husk ash as cement replacement in pervious concrete: A review. *Developments in the Built Environment*, 22, 100675. <https://doi.org/10.1016/J.DIBE.2025.100675>
- Khankhaje, E., Jang, H., Kim, J., & Rafieizonooz, M. (2025b). Utilizing rice husk ash as cement replacement in pervious concrete: A review. *Developments in the Built Environment*, 22. <https://doi.org/10.1016/j.dibe.2025.100675>
- Khankhaje, E., Kim, T., Jang, H., Kim, C. S., Kim, J., & Rafieizonooz, M. (2024). A review of utilization of industrial waste materials as cement replacement in pervious concrete: An alternative approach to sustainable pervious concrete production. In *Heliyon* (Vol. 10, Number 4). Elsevier Ltd. <https://doi.org/10.1016/j.heliyon.2024.e26188>
- Kumar, A., Bhattacharya, T., Shaikh, W. A., Roy, A., Chakraborty, S., Vithanage, M., & Biswas, J. K. (2023). Multifaceted applications of biochar in environmental management: a bibliometric profile. *Biochar*, 5(1). <https://doi.org/10.1007/s42773-023-00207-z>
- Le, D. L., Salomone, R., & Nguyen, Q. T. (2023). Circular bio-based building materials: A literature review of case studies and sustainability assessment methods. *Building and Environment*, 244. <https://doi.org/10.1016/j.buildenv.2023.110774>
- Legan, M., Gotvajn, A. Ž., & Zupan, K. (2022). Potential of biochar use in building materials. *Journal of Environmental Management*, 309. <https://doi.org/10.1016/j.jenvman.2022.114704>
- Li, S., & Tasnady, D. (2023). Biochar for Soil Carbon Sequestration: Current Knowledge, Mechanisms, and Future Perspectives. *C-Journal of Carbon Research*, 9(3). <https://doi.org/10.3390/c9030067>
- Luo, L., Wang, J., Lv, J., Liu, Z., Sun, T., Yang, Y., & Zhu, Y. G. (2023). Carbon Sequestration Strategies in Soil Using Biochar: Advances, Challenges, and Opportunities. *Environmental Science and Technology*, 57(31), 11357–11372. <https://doi.org/10.1021/acs.est.3c02620>
- Memon, S. A., Javed, U., Shah, M. I., & Hanif, A. (2022). Use of Processed Sugarcane Bagasse Ash in Concrete as Partial Replacement of Cement: Mechanical and Durability Properties. *Buildings*, 12(10). <https://doi.org/10.3390/buildings12101769>
- Montazeri, P., Bamshad, O., Aghililoft, M., & Singh, P. (2025). Mechanical and durability-based life cycle assessment of rice husk ash containing concrete. *Case Studies in Construction Materials*, 23, e05241. <https://doi.org/10.1016/J.CSCM.2025.E05241>
- Mujedu, K. A., Ab-Kadir, M. A., & Ismail, M. (2020). A review on self-compacting concrete incorporating palm oil fuel ash as a cement replacement. *Construction and Building Materials*, 258. <https://doi.org/10.1016/j.conbuildmat.2020.119541>
- Narayanan, S. K., & Kumar, N. (2025). Exploring the behaviour and performance of ashes of agricultural wastes for cleaner production in building materials: a systematic review. *Environmental Science and Pollution Research International*, 32(27), 16022–16050. <https://doi.org/10.1007/s11356-025-36674-z>
- Ngayakamo, B., & Onwualu, A. P. (2022). Recent advances in green processing technologies for valorisation of eggshell waste for sustainable construction materials. *Heliyon*, 8(6), e09649. <https://doi.org/10.1016/j.heliyon.2022.e09649>
- Nie, S., Zhou, J., Yang, F., Lan, M., Li, J., Zhang, Z., Chen, Z., Xu, M., Li, H., & Sanjayan, J. G. (2022). Analysis of theoretical carbon dioxide emissions from cement production: Methodology and application. *Journal of Cleaner Production*, 334. <https://doi.org/10.1016/j.jclepro.2021.130270>

- Nilimaa, J. (2023). Smart materials and technologies for sustainable concrete construction. *Developments in the Built Environment*, 15. <https://doi.org/10.1016/j.dibe.2023.100177>
- Olatoyan, O. J., Kareem, M. A., Adebajo, A. U., Olawale, S. O. A., & Alao, K. T. (2023). Potential use of biomass ash as a sustainable alternative for fly ash in concrete production: A review. *Hybrid Advances*, 4, 100076. <https://doi.org/10.1016/J.HYBADV.2023.100076>
- Olivia, M., Maulidi, M. A., Fadhilurrahman, & Wibisono, G. (2024). Characteristics of palm oil fuel ash concrete admixed with precipitated silica and silica fume. *Cleaner Engineering and Technology*, 19. <https://doi.org/10.1016/j.clet.2024.100738>
- Olsson, J. A., Miller, S. A., & Alexander, M. G. (2023). Near-term pathways for decarbonizing global concrete production. *Nature Communications*, 14(1). <https://doi.org/10.1038/s41467-023-40302-0>
- Onsongo, S. K., Olukuru, J., Munyao, O. M., & Mwabonje, O. (2025). The role of agricultural ashes (rice husk ash, coffee husk ash, sugarcane bagasse ash, palm oil fuel ash) in cement production for sustainable development in Africa. *Discover Sustainability* 2025 6:1, 6(1), 62-. <https://doi.org/10.1007/s43621-025-00841-6>
- Osman, A. I., Fawzy, S., Farghali, M., El-Azazy, M., Elgarahy, A. M., Fahim, R. A., Maksoud, M. I. A. A., Ajlan, A. A., Yousry, M., Saleem, Y., & Rooney, D. W. (2022). Biochar for agronomy, animal farming, anaerobic digestion, composting, water treatment, soil remediation, construction, energy storage, and carbon sequestration: a review. *Environmental Chemistry Letters*, 20(4), 2385–2485. <https://doi.org/10.1007/s10311-022-01424-x>
- Overmann, S., Allwicher, I., Montag, D., Vollpracht, A., & Matschei, T. (2025). Comparative Evaluation of Different Biomass Ashes as Supplementary Cementitious Materials: Reactivity, Hydration Impact and Environmental Considerations. *Materials*, 18(18). <https://doi.org/10.3390/ma18184239>
- Oyejobi, D. O., Firoozi, A. A., Fernández, D. B., & Avudaiappan, S. (2024). Integrating circular economy principles into concrete technology: Enhancing sustainability through industrial waste utilization. *Results in Engineering*, 24(1), 102846. <https://doi.org/10.1016/j.rineng.2024.102846>
- Ozturk, E., Ince, C., Derogar, S., & Ball, R. (2022). Factors affecting the CO₂ emissions, cost efficiency and eco-strength efficiency of concrete containing rice husk ash: A database study. *Construction and Building Materials*, 326. <https://doi.org/10.1016/j.conbuildmat.2022.126905>
- Park, C., & Lee, J. (2024). Transforming biowaste into sustainable supplementary cementitious materials. *Journal of Building Engineering*, 98. <https://doi.org/10.1016/j.jobbe.2024.110976>
- Petroche, D. M., & Ramirez, A. D. (2022). The Environmental Profile of Clinker, Cement, and Concrete: A Life Cycle Perspective Study Based on Ecuadorian Data. *Buildings*, 12(3). <https://doi.org/10.3390/buildings12030311>
- Qaidi, S., Najm, H. M., Abed, S. M., Ahmed, H. U., Al Dughaiishi, H., Al Lawati, J., Sabri, M. M., Alkhatib, F., & Milad, A. (2022). Fly Ash-Based Geopolymer Composites: A Review of the Compressive Strength and Microstructure Analysis. *Materials*, 15(20). <https://doi.org/10.3390/ma15207098>
- Sakir, S., Raman, S. N., Safiuddin, M., Amrul Kaish, A. B. M., & Mutalib, A. A. (2020). Utilization of by-products and wastes as supplementary cementitious materials in structural mortar for sustainable construction. *Sustainability (Switzerland)*, 12(9). <https://doi.org/10.3390/su12093888>
- Senadheera, S. S., Gupta, S., Kua, H. W., Hou, D., Kim, S., Tsang, D. C. W., & Ok, Y. S. (2023). Application of biochar in concrete – A review. *Cement and Concrete Composites*, 143, 105204. <https://doi.org/10.1016/J.CEMCONCOMP.2023.105204>
- Shah, I. H., Miller, S. A., Jiang, D., & Myers, R. J. (2022). Cement substitution with secondary materials can reduce annual global CO₂ emissions by up to 1.3 gigatons. *Nature Communications*, 13(1). <https://doi.org/10.1038/s41467-022-33289-7>
- Shakouri, M., Exstrom, C. L., Ramanathan, S., Suraneni, P., & Vaux, J. S. (2020). Pretreatment of corn stover ash to improve its effectiveness as a supplementary cementitious material in concrete. *Cement and Concrete Composites*, 112, 103658. <https://doi.org/10.1016/J.CEMCONCOMP.2020.103658>
- Siddiq, M. U., Anwar, M. K., Almansour, F. H., Qurashi, M. A., & Adeel, M. (2025). AI-Driven Optimization of Fly Ash-Based Geopolymer Concrete for Sustainable High Strength and CO₂

- Reduction: An Application of Hybrid Taguchi–Grey–ANN Approach. *Buildings*, 15(12). <https://doi.org/10.3390/buildings15122081>
- Snellings, R., Suraneni, P., & Skibsted, J. (2023). Future and emerging supplementary cementitious materials. *Cement and Concrete Research*, 171. <https://doi.org/10.1016/j.cemconres.2023.107199>
- Suarez-Riera, D., Restuccia, L., & Ferro, G. A. (2020). The use of Biochar to reduce the carbon footprint of cement-based materials. *Procedia Structural Integrity*, 26, 199–210. <https://doi.org/10.1016/J.PROSTR.2020.06.023>
- Suomie, R. W., Mishra, B. P., & Das, S. (2025). Performance of rice husk ash (RHA) and recycled coarse aggregate (RCA) for sustainable concrete: A review. *Next Materials*, 8, 100778. <https://doi.org/10.1016/J.NXMATE.2025.100778>
- Supriya, Chaudhury, R., Sharma, U., Thapliyal, P. C., & Singh, L. P. (2023). Low-CO2 emission strategies to achieve net zero target in cement sector. *Journal of Cleaner Production*, 417. <https://doi.org/10.1016/j.jclepro.2023.137466>
- Thomas, B. S., Yang, J., Mo, K. H., Abdalla, J. A., Hawileh, R. A., & Ariyachandra, E. (2021). Biomass ashes from agricultural wastes as supplementary cementitious materials or aggregate replacement in cement/geopolymer concrete: A comprehensive review. *Journal of Building Engineering*, 40. <https://doi.org/10.1016/j.jobe.2021.102332>
- Tran, C. N. N., Illankoon, I. M. C. S., & Tam, V. W. Y. (2025). Decoding Concrete’s Environmental Impact: A Path Toward Sustainable Construction. *Buildings*, 15(3). <https://doi.org/10.3390/buildings15030442>
- Yang, M., Chen, L., Lai, J., Osman, A. I., Farghali, M., Rooney, D. W., & Yap, P. S. (2024). Advancing environmental sustainability in construction through innovative low-carbon, high-performance cement-based composites: A review. In *Materials Today Sustainability* (Vol. 26). Elsevier Ltd. <https://doi.org/10.1016/j.mtsust.2024.100712>
- Yaseen, N. (2024). Exploring the potential of sugarcane bagasse ash as a sustainable supplementary cementitious material: Experimental investigation and statistical analysis. *Results in Chemistry*, 10, 101723. <https://doi.org/10.1016/J.RECHEM.2024.101723>
- Yin, X., Rahman, M. M., Sun, Y., Zhao, Y., & Wang, J. (2025). Sustainable Soil–Cement Composites with Rice Husk Ash and Silica Fume: A Review of Performance and Environmental Benefits. *Materials*, 18(12). <https://doi.org/10.3390/ma18122880>
- Zhao, Z., El-Naggar, A., Kau, J., Olson, C., Tomlinson, D., & Chang, S. X. (2024). Biochar affects compressive strength of Portland cement composites: a meta-analysis. *Biochar*, 6(1). <https://doi.org/10.1007/s42773-024-00309-2>



ICRES26_066

CONCRETE MATERIAL MODEL FOR PULVERIZED CONCRETE PARTICULATES

P.M.B.P.D. Dayarathne*

Department of Civil Engineering, Faculty of Engineering, General Sir John Kotelawala Defence University, Kandawala Rd, Ratmalana, Sri Lanka

**Correspondence E-mail: 39-eng-0086@kdu.ac.lk, TP: +94763749059*

Abstract: The mounting pile of demolished concrete has driven the need for precise material models that can capture how recycled concrete particulates behave under pressure. This research introduces a constitutive model for pulverized concrete particles subjected to three-dimensional stress. To collect the data, cubic specimens were compacted and analyzed in a triaxial test apparatus, which allowed for independent control over the three principal stresses (σ_1 , σ_2 , σ_3). Throughout various stress paths, the team recorded stress–strain responses, volumetric shifts, and particle crushing. These experimental findings were then used to build Haigh-Westergaard failure surfaces within MATLAB. Ultimately, these results served as the foundation for a 3D constitutive model designed to predict how pulverized concrete performs in practical engineering, from backfill and ground improvement to recycled-aggregate design. This proposed model offers a functional framework for numerical simulations and promotes the sustainable reuse of concrete waste.

Keywords: Pulverized concrete; Triaxial test apparatus; Haigh-Westergaard (Vestergaard) failure surface; principal stresses; MATLAB Software

1. Introduction

The construction industry ranks among the world's largest consumers of natural resources and remains a major contributor to landfill waste. Construction and demolition waste (CWD) is generated globally, consisting of materials like RCA, brick, plaster, gypsum, glass, asphalt, stone, steel, Fiber, and polymers. Notably, recycled concrete makes up a significant portion about 80% of this waste [20]. Consequently, the push toward a circular economy has sparked extensive research into recycling end-of-life concrete. While the use of coarse recycled aggregate (CRA) is now relatively well-established, a more pressing challenge persists how to effectively use the fine, pulverized fraction of crushed concrete. These pulverized concrete particulates (PCPs) are often dismissed as a problematic byproduct, yet they possess unique traits such as high porosity and a large surface area from residual cement paste that fundamentally change the properties of new concrete. A lack of precise understanding regarding how these particulates influence mechanical behaviour has been the primary barrier to their use in structural applications. Standard material models designed for conventional concrete, or even those modified for CRA, fail to accurately predict the stress-strain response, modulus of elasticity, and post-peak behaviour of concrete containing PCPs. This research addresses that critical gap by developing a dedicated Concrete Material Model for Pulverized Concrete Particulates. The goal is to formulate a robust model that captures the composite mechanical behaviour of PCP-based concrete, giving engineers the tools they need to confidently design and analyse structures using this sustainable material.



Figure 1: Concrete Wastage

The global construction industry is at a critical crossroads, caught between skyrocketing infrastructure demands and the urgent pressure to shrink its massive environmental footprint. As the most widely used man-made material on Earth, concrete consumes a staggering amount of virgin aggregates and remains a major contributor to the world's landfills. Turning construction and demolition (C&D) waste into recycled concrete aggregates (RCA) is now a cornerstone of the industry's shift toward a circular economy. However, the crushing process produces more than just coarse RCA; it also generates vast quantities of fine "pulverized concrete particulates" (PCPs). While coarse RCA has gained some level of acceptance, PCPs are still largely dismissed as a problematic waste product, typically downcycled into low-value road base or landfill.

The main technical hurdle to using PCPs in high-value concrete is their porous, composite nature. Unlike clean, inert natural sand, PCPs consist of original fine aggregate particles encased in a weaker, porous matrix of leftover hydrated cement paste. This leads to significantly higher water absorption, which necessitates higher water-cement ratios, creates weaker Interfacial Transition Zones (ITZs), and generally degrades the mechanical performance of the resulting concrete.

To date, most research on PCP-concrete focuses on its performance under simple, uniaxial compression essentially standard cube or cylinder tests. While useful, these tests fail to capture how the material behaves under the complex, multiaxial stress states found in real-world structures like foundations, retaining walls, dams, and elements in seismic zones. In these applications, the concrete is subjected to a confining pressure (σ_3) that significantly influences its ultimate strength (σ_1) and ductility.

For a new, quasi-brittle composite like PCP concrete, a basic uniaxial strength value isn't enough for structural design. Instead, engineers need a comprehensive material model that describes how the material fails under combined shear and normal stresses. The Mohr-Coulomb failure criterion a staple in soil and rock mechanics is perfectly suited for this. It defines strength using two key parameters: cohesion (c) and the internal friction angle (ϕ), which together explain exactly how the material gains strength under confinement.

Consequently, this research moves past simple uniaxial testing. We use a rock triaxial apparatus to subject cylindrical PCP concrete samples to various confining pressures (σ_3) and record the peak axial stress (σ_1) at the point of failure. These principal stress pairs are then mapped onto the Vestergaard stress plane. This specific transformation offers a powerful way to linearize the failure envelope, making it possible to determine the (c) and ϕ parameters precisely through regression analysis.

A major gap remains in current literature, as these specific parameters for PCP-based concrete are largely unknown. By systematically deriving these values, this research develops a robust material model. Implemented via MATLAB, this model provides the data necessary for engineers to safely integrate pulverized concrete particulates into structural design software, finally turning a waste product into a high-value resource.

2. Objectives

- I. Prepare pulverized concrete particulate samples with controlled particle size distribution.
- II. Conduct rock triaxial tests on cubic specimens to obtain stress–strain behaviour under various stress paths.
- III. Measure principal stresses ($\sigma_1, \sigma_2, \sigma_3$) and corresponding strains to identify failure modes.
- IV. Develop Vestergaard (Haigh-Westergaard) failure envelopes from test data.

3. Literature Review

The construction industry is currently facing a massive waste crisis. Cement-based materials are among the most common man-made products on Earth [10]. While the use of recycled aggregate from construction and demolition waste (CDW) to replace natural sand and gravel has grown lately [1], most of this material still ends up in landfills. This research aims to find a practical way to reuse this waste powder in new structural concrete.

Before engineers can use this "PCP concrete," they need to know exactly how it behaves under real-world conditions—not just during simple crushing, but under complex, multi-directional pressures. This critical strength data, known as a material model, simply doesn't exist yet.

Our study will be the first to develop this essential model. We will test PCP concrete samples in a rock triaxial machine to measure their true strength under confinement. Then, we will analyze this data using MATLAB to build a reliable model that finally lets engineers design sustainable structures using this recycled material



Figure 2: Construction and Demolished Wastage

3.1 Rock Triaxial Test

In geotechnical engineering, the triaxial test serves as a fundamental technique for determining the mechanical properties and shear strength of materials like rock, soil, and granular particles. Its primary goal is to replicate the underground (in-situ) stress conditions that a material naturally encounters.

During the test, a cylindrical specimen is placed inside a high-pressure cell where a fluid exerts a uniform confining pressure (σ_3). Next, a separate, increasing axial load (σ_1) is applied vertically until the specimen fails. For testing hard rock, a specialized, high-stiffness device known as a rock triaxial apparatus is used to withstand the intense pressures required. This method establishes the material's strength characteristics and, when paired with deformation measurements, provides the full stress-strain data needed to calculate elastic properties like Young's modulus and Poisson's ratio



Figure 3: Rock Triaxial Apparatus



Figure 4: Mould & Testing Sample

4. Methodology

The research methodology began with a comprehensive literature review to establish suitable procedures and investigate current applications for pulverized concrete. This was followed by an in-depth theoretical analysis of failure planes, Westergaard stress planes, and principal stresses. Based on these findings, an appropriate range of replacement ratios was determined, and concrete cubes were cast at those specific levels for a 28-day curing period. After curing, samples were cored from the cubes and subjected to compressive strength and rock triaxial testing to gather empirical data. Finally, these results were analysed to develop a predictive material model using MATLAB software.

5. Results and Discussion

5.1 Workability



Figure 5: Slump test

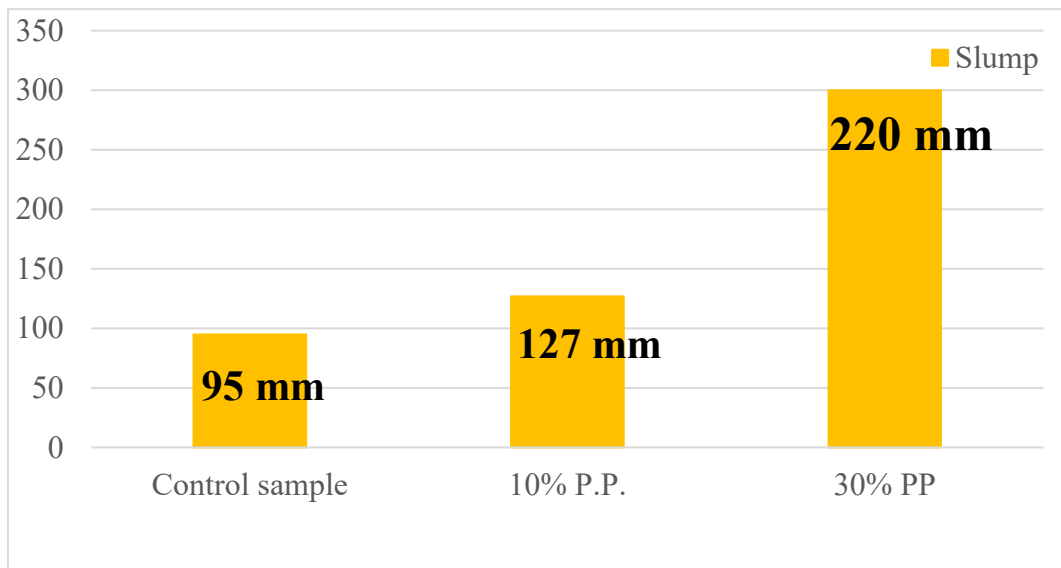


Figure 6: Slump test Results

Slump increased with increasing PP content. This happens for two reasons.

First, the pulverized particulates are highly porous and act like sponges, absorbing the free mixing water immediately.

Second, the particles are more angular than natural sand, which creates higher internal friction.

5.2 Rock Triaxial Data

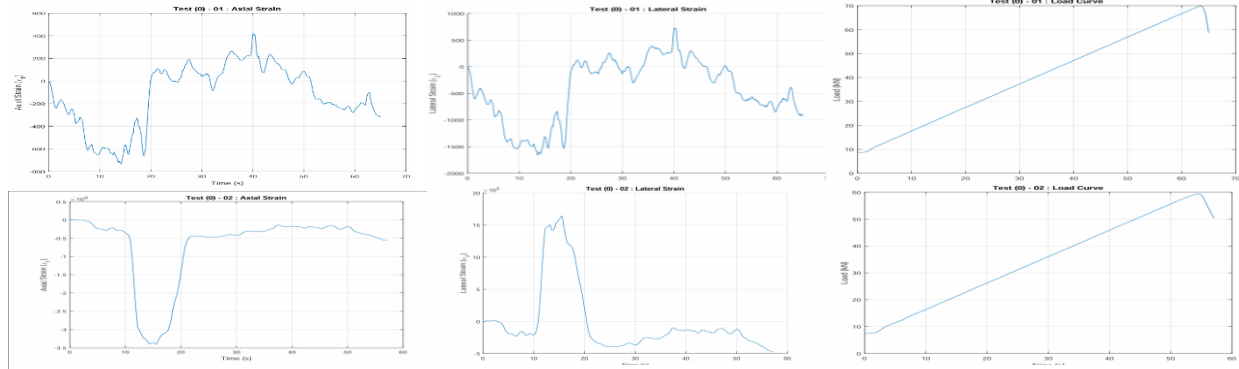


Figure 7: Axial strain, Lateral strain and Load curve of Control Sample

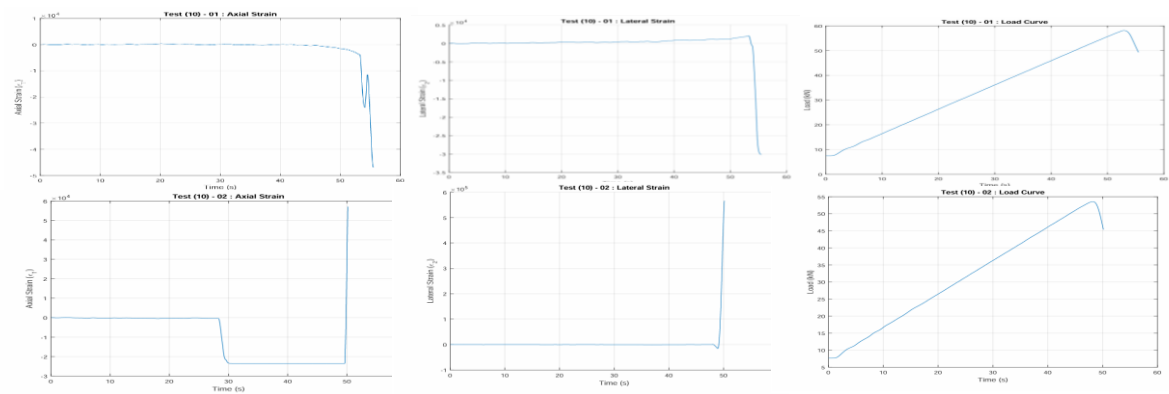


Figure 8: Axial strain, Lateral strain and Load curve of 10% Sample

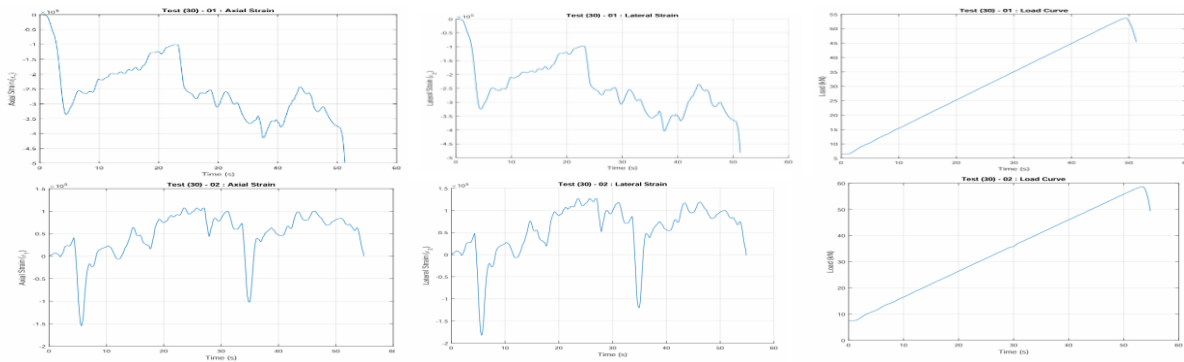


Figure 9: Axial strain, Lateral strain and Load curve of 30% Sample

To mathematically describe our material, we use a Constitutive Model, which specifies how the material deforms under load. While there are complex models like Mohr-Coulomb—which we used for failure analysis, the simplest baseline for any rock mass is the Linear Isotropic Elastic model. This follows Hooke's Law, assuming that strain is directly proportional to stress, linking the 6 stress and strain components in a linear matrix;

$$\epsilon_x = \frac{1}{E} [\sigma_x - \nu(\sigma_y + \sigma_z)] \quad (1)$$

$$\epsilon_y = \frac{1}{E} [\sigma_y - \nu(\sigma_x + \sigma_z)] \quad (2)$$

$$\epsilon_z = \frac{1}{E} [\sigma_z - \nu(\sigma_x + \sigma_y)] \quad (3)$$

$$\gamma_{xy} = \frac{1}{G} \tau_{xy} \quad (4)$$

K= Bulk Modulus

$$\epsilon_{vol} = \epsilon_x + \epsilon_y + \epsilon_z$$

$$\epsilon_{vol} = \frac{1-2\nu}{E} [\sigma_x + \sigma_y + \sigma_z]$$

$$\epsilon_{vol} = \frac{3(1-2\nu)}{E} \frac{[\sigma_x + \sigma_y + \sigma_z]}{3} = \frac{1}{K} \frac{[\sigma_x + \sigma_y + \sigma_z]}{3}$$

$$\begin{Bmatrix} \epsilon_x \\ \epsilon_y \\ \epsilon_z \\ \gamma_{xy} \\ \gamma_{yz} \\ \gamma_{zx} \end{Bmatrix} = \frac{1}{E} \begin{bmatrix} 1 & -\nu & -\nu & 0 & 0 & 0 \\ -\nu & 1 & -\nu & 0 & 0 & 0 \\ -\nu & -\nu & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 2(1+\nu) & 0 & 0 \\ 0 & 0 & 0 & 0 & 2(1+\nu) & 0 \\ 0 & 0 & 0 & 0 & 0 & 2(1+\nu) \end{bmatrix} \begin{Bmatrix} \sigma_x \\ \sigma_y \\ \sigma_z \\ \tau_{xy} \\ \tau_{yz} \\ \tau_{zx} \end{Bmatrix}$$

$$\begin{Bmatrix} \sigma_x \\ \sigma_y \\ \sigma_z \\ \tau_{xy} \\ \tau_{yz} \\ \tau_{zx} \end{Bmatrix} = \frac{E}{(1+\nu)(1-2\nu)} \begin{bmatrix} 1-\nu & \nu & \nu & 0 & 0 & 0 \\ \nu & 1-\nu & \nu & 0 & 0 & 0 \\ \nu & \nu & 1-\nu & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{(1-2\nu)}{2} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{(1-2\nu)}{2} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{(1-2\nu)}{2} \end{bmatrix} \begin{Bmatrix} \epsilon_x \\ \epsilon_y \\ \epsilon_z \\ \gamma_{xy} \\ \gamma_{yz} \\ \gamma_{zx} \end{Bmatrix}$$

$$E_1 \epsilon_{11} = \sigma_{11} - \nu(\sigma_{22} + \sigma_{22}) \quad (8)$$

$$E_2 \epsilon_{22} = \sigma_{22} - \nu(\sigma_{11} + \sigma_{22}) \quad (9)$$

Solving for σ_{11} and σ_{22} gives,

$$\sigma_{22} = \frac{\nu E_1 \epsilon_{11} + E_2 \epsilon_{22}}{1 - \nu - \nu^2} \quad (10)$$

$$\sigma_{11} = E_1 \epsilon_{11} + 2\nu \sigma_{22} \quad (11)$$

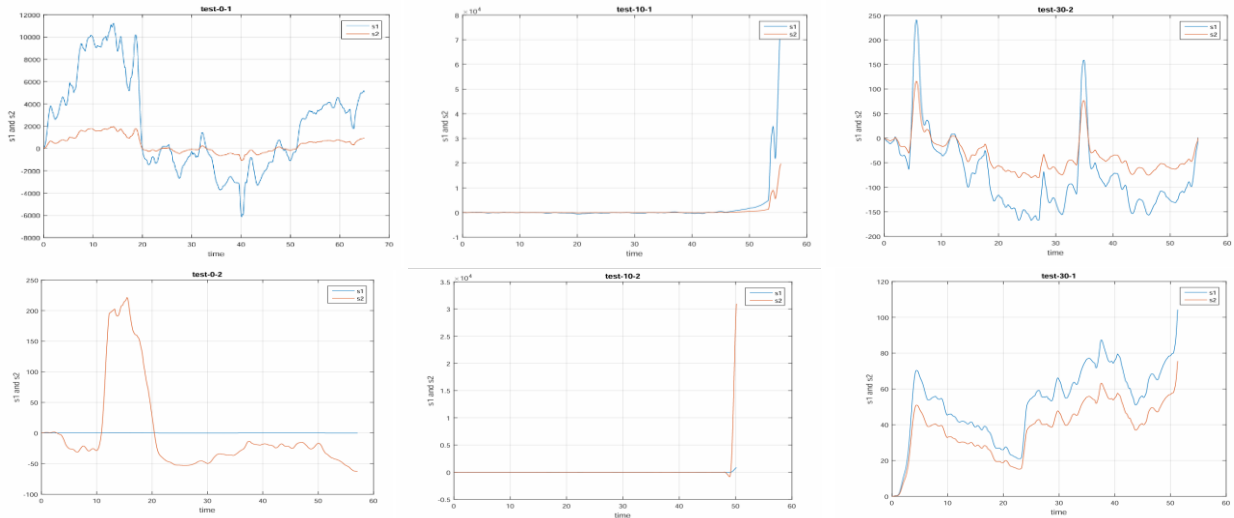


Figure 10: Stress Results Graph

Table 1: Stress Results

Test No.	σ_{11} (MPa)	σ_{22} (MPa)	$\sigma_{33} = \sigma_{22}$ (MPa)	Max Load (kN)
Test_01	11240	1958	1958	69.7
Test_02	0.445	221	221	59.4
Test_10_1	76585	19717	19717	58.1
Test_10_2	847	30953	30953	53.5
Test_30_1	104.2	75.4	75.4	53.6
Test_30_2	240.7	115.8	115.8	58.6

5.3 Discussion

Experimental inconsistencies prevent the inclusion of a representation of the final model in the Vestergaard stress plane. Unreliable lateral strain data were caused by problems with signal noise, machine calibration, and strain-gauge orientation. Furthermore, the accurate stress calculation needed for such high-fidelity modelling was made impossible by the absence of instantaneous cross-sectional area measurements.

6 Conclusion

- Pulverized particulates rely heavily on mechanical interlocking (friction) rather than cement paste cohesion.
- The Mohr-Coulomb Criterion was successfully substantiated as the most appropriate model for predicting this shear behaviour.
- Current standard rock mechanics instrumentation is insufficient for complex 3D failure surface mapping.

Acknowledgements

First and foremost, I wish to convey my sincere appreciation to the Vice Chancellor and the Academic staff for providing me an opportunity to accomplish research which is going to be a milestone of my professional career. The hassles I faced in conducting this research were of numerous folds. If not for the assistance extended by many great personalities and institutions, such would have ruined the effort. Therefore, I am very grateful to those who guided and supported me throughout this work.

At the outset, my profound gratefulness goes to Eng. K.M. Vignarajha, Senior Lecturer, Department of Civil Engineering, Faculty of Engineering, General Sir John Kotelawala Defence University, who supervised and inspired me with her expertise during research work and without whom this research work would not have been a success. Further, the guidance and the support always given by the lecturers in the Department of Civil Engineering is highly appreciated.

I would also like to thank all the technical officers and lab assistants in the civil engineering department for their support from the beginning of the research, as well as the workshop staff. Also, to all those who have not been specifically mentioned here, through their relentless support during the period of the research, success would not have been a reality. Finally, words of thanks should be extended to my lovely parents and sister for the immense moral support and material input given to achieve the goal of this research.

References

- [1] Kovacs, R., Shamass, R. and Limbachiya, V. (2025). Multi-recycling of different concrete products: Effects on recycled aggregate's physical characteristics and compressive strength. *Journal of Building Engineering*, [online] 113, p.114004. doi:<https://doi.org/10.1016/j.jobe.2025.114004>.
- [2] Li, J., Hong, J., Liu, S., Zhou, Y. and Meng, K. (2023). Multiaxial compressive strength of hybrid fiber reinforced concrete: A unified empirical model. *Frontiers in Materials*, 10. doi:<https://doi.org/10.3389/fmats.2023.1100868>.
- [3] Úcar, R., Arlegui, L., Belandria, N. and Torrijo, F. (2024). Estimating rock strength parameters across varied failure criteria: Application of spreadsheet and R-based orthogonal regression to triaxial test data. *Journal of Rock Mechanics and Geotechnical Engineering*, [online] 17(8), pp.4685–4699. doi:<https://doi.org/10.1016/j.jrmge.2024.11.024>.
- [4] Feng, X.-T., Zhang, J., Yang, C., Tian, J., Lin, F., Li, S. and Su, X. (2021). A novel true triaxial test system for microwave-induced fracturing of hard rocks. *Journal of Rock Mechanics and Geotechnical Engineering*, 13(5), pp.961–971. doi:<https://doi.org/10.1016/j.jrmge.2021.03.008>.
- [5] Óchsner, A. (2024). *Plasticity Theory*. Springer Nature.
- [6] Tanaka, H. (2023). *Elasto-Plastic Damage Behaviour of Concrete Elements*. CRC Press.
- [7] Aghani, K. and Farahmand-Tabar, S. (2024). Seismic fragility assessment of the innovative and optimal box-shaped dampers in steel frame structures. *Soil Dynamics and Earthquake Engineering*, 180, p.108623. doi:<https://doi.org/10.1016/j.soildyn.2024.108623>.
- [8] Zang, R., Hao, Z., Zhang, K., Xu, B., Tam, V.W.Y. and Bompa, D.V. (2025). Triaxial constitutive modelling and failure criteria of rubberised concrete materials. *Journal of Building Engineering*, [online] 105, p.112460. doi:<https://doi.org/10.1016/j.jobe.2025.112460>.
- [9] Manzi, S., Mazzotti, C. and Bigozzi, M.C. (2013). Short and long-term behavior of structural concrete with recycled concrete aggregate. *Cement and Concrete Composites*, 37, pp.312–318. doi:<https://doi.org/10.1016/j.cemconcomp.2013.01.003>.
- [10] Google Books. (2025). *Plasticity in Reinforced Concrete*. [online] Available at: https://books.google.com.sg/books/about/Plasticity_in_Reinforced_Concrete.html?id=FGp-U4hNjggC&redir_esc=y [Accessed 9 Nov. 2025].
- [11] Wang, S., Zhong, Z., Chen, B., Liu, X. and Wu, B. (2022). Developing a Three Dimensional (3D) Elastoplastic Constitutive Model for Soils Based on Unified Nonlinear Strength (UNS) Criterion. *Frontiers in Earth Science*, 10. doi:<https://doi.org/10.3389/feart.2022.853962>.
- [12] Lapyote Prasittisopin, Wiput Tuvayanond, Kang, T.H.-K. and Sakdirat Kaewunruen (2025). Concrete Mix Design of Recycled Concrete Aggregate (RCA): Analysis of Review Papers, Characteristics, Research Trends, and Underexplored Topics. *Resources*, [online] 14(2), pp.21–21. doi:<https://doi.org/10.3390/resources1402021>.



ICRES

International Conference on
Resource Efficiency Towards Sustainability

**International Conference on
Resource Efficiency Towards Sustainability**

**RESOURCE EFFICIENCY IN ENERGY, WATER,
AND SUPPLY CHAINS**

ICRES26_007

COMPARATIVE EVALUATION OF NATURAL MINERAL PHOTOCATALYSTS FOR SUSTAINABLE WASTEWATER TREATMENT USING MCDM APPROACH

S. M. Gamage*, A. M. Wasantha

Department of Chemical and Process Engineering, Faculty of Engineering, University of Peradeniya

**Correspondence E-mail: e18107@eng.pdn.ac.lk, TP: +94760887671*

Abstract: The growing contamination of water bodies by industrial dyes has created a critical demand for sustainable and efficient wastewater treatment technologies. Photocatalysis is a promising approach that can completely degrade organic pollutants under light irradiation, offering an environmentally friendly solution. Conventional synthetic photocatalysts such as titanium dioxide (TiO_2) and zinc oxide (ZnO) are effective but costly to synthesize and limited by their environmental footprint. Natural minerals provide an attractive alternative due to their abundance, stability, and intrinsic photocatalytic properties. This study evaluated three natural minerals, ilmenite (FeTiO_3), hematite (Fe_2O_3), and natural rutile (TiO_2), as potential photocatalysts for dye degradation. Six criteria were considered: photocatalytic activity, band gap energy, resource abundance, cost and processing requirement, environmental sustainability, and stability. The analysis was conducted using the PROMETHEE multi-criteria decision-making (MCDM) approach in Visual PROMETHEE software. Results showed that ilmenite achieved the highest net preference flow ($\Phi = 0.2500$), followed by hematite ($\Phi = 0.1500$) and natural rutile ($\Phi = -0.4000$). Ilmenite exhibited a favourable balance between efficiency, cost, and sustainability, making it the most suitable mineral photocatalyst. The study highlights the potential of ilmenite for low-cost and eco-friendly wastewater treatment applications and demonstrates the usefulness of MCDM methods for rational material selection in sustainable water treatment.

Keywords: Photocatalysis, Ilmenite, Hematite, Rutile, PROMETHEE, Wastewater Treatment

1. Introduction

Water contamination from synthetic dyes has emerged as a major environmental and public health issue worldwide. Rapid industrialization, particularly in the textile, printing, leather, and paper sectors, has resulted in the continuous discharge of large quantities of dye-containing wastewater into aquatic systems (Periyasamy et al., 2024). These dyes are designed to resist degradation by light, heat, and microbial activity, making them persistent and difficult to remove by conventional treatment processes. Many are toxic, mutagenic, or carcinogenic, posing long-term ecological risks and health hazards (Tchounwou et al., 2004). Conventional treatment techniques such as coagulation, adsorption, and membrane filtration can remove dyes physically but fail to achieve complete degradation, often transferring pollutants from water to solid waste streams (Hanafi et al., 2020).

Photocatalysis, a type of advanced oxidation process (AOP), has gained significant attention as an efficient and sustainable method for degrading organic contaminants. It utilizes light energy to activate semiconductor materials that generate electron-hole pairs, which subsequently form reactive oxygen species capable of oxidizing pollutants into harmless compounds such as CO_2 and H_2O (Andreozzi et al., 1999). This process offers several advantages, including operation under mild conditions, potential for solar activation, and minimal chemical input. The performance of a photocatalyst depends primarily on its band gap, charge carrier mobility, surface area, and chemical stability (Liu et al., 2020).

Titanium dioxide (TiO_2) has long been recognized as one of the most efficient photocatalysts due to its strong oxidative power, photochemical stability, and low toxicity (Ijaz et al., 2021). However, synthetic TiO_2 production involves high-temperature calcination, use of expensive precursors, and limited absorption of visible light because of its wide band gap of approximately 3.2 eV. These limitations hinder its large-scale application, especially in developing countries where cost and sustainability are key factors (Racovita et al., 2022). Consequently, attention has shifted toward naturally occurring minerals that possess intrinsic photoactive properties and are abundantly available at low cost (Zhao et al., 2024).

Natural minerals such as ilmenite (FeTiO_3), hematite (Fe_2O_3), and rutile (TiO_2) contain metal oxides capable of generating charge carriers under light irradiation (Usgodaarachchi et al., 2022). These materials can be directly used or minimally processed to function as efficient photocatalysts. Ilmenite, a mixed iron-titanium oxide, exhibits a pseudo-rutile crystal structure and contains both Ti^{4+} and Fe^{2+} ions. The $\text{Fe}^{2+}/\text{Fe}^{3+}$ redox cycle plays a crucial role in enhancing electron-hole separation and suppressing recombination, which significantly improves photocatalytic activity (Guo et al., 2022). Hematite, an iron oxide mineral with a band gap of about 2.1 eV, absorbs visible light effectively and is among the most abundant semiconductors in nature (Wan et al., 2023). However, its poor conductivity and short carrier diffusion length often limit efficiency unless modified through doping or nanostructuring (Saremi-Yarahmadi et al., 2010). Natural rutile, a mineral form of TiO_2 , exhibits excellent chemical stability and high oxidation potential, yet its relatively large band gap restricts visible-light utilization and requires ultraviolet irradiation (Li et al., 2018).

Utilizing such minerals directly as photocatalysts represents an important step toward the circular economy and resource efficiency. Natural minerals are widely distributed, non-toxic, and require minimal processing, which reduces both economic cost and carbon footprint. Their valorization not only provides an eco-friendly alternative to synthetic catalysts but also enhances the economic value of locally available raw materials (Ngulube et al., 2024). For instance, ilmenite deposits in Sri Lanka and other coastal regions offer substantial potential for sustainable wastewater treatment technologies based on indigenous resources (Subasinghe et al., 2022). This approach integrates environmental protection, material sustainability, and local economic development, contributing directly to United Nations Sustainable Development Goal 6 on clean water and sanitation.

The exploration and comparison of ilmenite, hematite, and natural rutile as photocatalysts provide valuable insight into the feasibility of natural mineral utilization for dye degradation. Their performance

is influenced by multiple interrelated factors such as photocatalytic efficiency, band structure, resource availability, cost, toxicity, and durability. A balanced evaluation of these parameters is essential for identifying the most sustainable and effective mineral catalyst for large-scale wastewater remediation.

2. Common Photocatalysts for Wastewater Treatment

Photocatalysis has been widely investigated as a promising technique for the degradation of organic pollutants in wastewater due to its ability to completely mineralize complex dye molecules into harmless products using light energy. Over the past decades, a variety of semiconductor photocatalysts have been developed, primarily based on metal oxides, sulfides, and nitrides. These materials differ in electronic structure, light absorption range, and stability, which influence their photocatalytic performance and suitability for practical applications (Shareef et al., 2023).

Among the most extensively studied photocatalysts, titanium dioxide (TiO_2) remains the standard due to its high stability and strong oxidative ability, although it is limited to ultraviolet activation. Other semiconductors such as zinc oxide (ZnO), hematite (Fe_2O_3), bismuth vanadate (BiVO_4), graphitic carbon nitride ($g\text{-C}_3\text{N}_4$), and cadmium sulfide (CdS) have also shown significant potential. However, each material faces distinct challenges such as photocorrosion, toxicity, narrow absorption range, or complex synthesis routes (Barzagan et al., 2022; Ameta et al., 2016). Table 2.1 summarizes the key properties, advantages, and limitations of commonly used photocatalysts for wastewater treatment. This comparative overview highlights the need for exploring naturally available minerals as sustainable, low-cost, and environmentally benign alternatives.

Table 2.1: Summary of common photocatalysts used in wastewater treatment

Photocatalyst	Band Gap (eV)	Light Response	Advantages	Limitations	References
TiO_2 (anatase)	3.2	UV	Stable, non-toxic, cheap	Only UV-active	(Barzagan et al., 2022)
ZnO	3.2	UV	High activity, available	Photocorrosion in water	(Barzagan et al., 2022)
BiVO_4	2.4	Visible	Good visible absorption	Low electron mobility	(Barzagan et al., 2022)
$g\text{-C}_3\text{N}_4$	2.7	Visible	Metal-free, solar-active	Low surface area	(Barzagan et al., 2022)
CdS	2.4	Visible	Strong absorption	Toxicity, instability	(Barzagan et al., 2022)

3. Natural Minerals as Photocatalysts

Natural minerals provide an excellent route for sustainable photocatalysis since they occur abundantly in nature, often require minimal processing, and possess inherent photoactive metal oxides. Among them, ilmenite (FeTiO_3), hematite (Fe_2O_3), and rutile (TiO_2) are of particular interest for wastewater treatment (Mishra et al., 2023).

3.1 Ilmenite (FeTiO_3)

Ilmenite combines titanium and iron in a rhombohedral crystal structure similar to pseudo-rutile. The $\text{Fe}^{2+}/\text{Fe}^{3+}$ redox couple enhances electron transfer and suppresses recombination of photogenerated carriers, increasing degradation efficiency (Mishra et al., 2023). Ilmenite typically exhibits a band gap of 2.5–2.7 eV, enabling partial visible-light absorption. Its natural abundance and low cost make it an attractive candidate for large-scale photocatalytic processes.

3.2 Hematite (Fe_2O_3)

Hematite has a narrow band gap (~2.1 eV) and strong visible-light absorption capacity. It is among the most abundant semiconducting minerals on Earth and is non-toxic. However, its photocatalytic performance is often limited by high charge recombination rates and poor electron mobility, which

restrict reaction kinetics (Moattari et al., 2025). Surface modification, nanostructuring, and heterojunction formation can improve its efficiency.

3.3 Natural Rutile (TiO₂)

Natural Rutile is a crystalline form of titanium dioxide, that exhibits exceptional chemical stability, hardness, and oxidative power. Its band gap (~3.0 eV) restricts visible-light absorption, but its robustness and high degradation potential make it a common natural benchmark (Žerjav et al., 2022). Natural rutile often contains trace Fe or Mn, which can slightly enhance charge transfer efficiency compared to pure synthetic TiO₂.

4. Comparison Parameters for Photocatalytic Evaluation

To evaluate and select the most effective natural photocatalyst, several measurable parameters can be used (Mei et al., 2023). Six critical criteria commonly applied in multi-criteria decision-making (MCDM) approaches are outlined below.

4.1. Photocatalytic Activity / Degradation Efficiency

This criterion represents the ability of a mineral to degrade organic pollutants under light irradiation. It is quantified as a percentage of degradation or as a reaction rate constant (*k*). For dyes such as methylene blue or rhodamine B, high-performance catalysts exhibit >80% degradation within 60–120 min under UV or visible light (Gusain et al., 2020).

4.2. Band Gap Energy and Electronic Structure

An ideal photocatalyst has a band gap between 1.8 and 3.0 eV, allowing activation under visible light while maintaining strong redox potential (Gusain et al., 2020; Moattari et al., 2025). Smaller band gaps improve solar utilization but can increase recombination; hence, balanced electronic structure is crucial.

4.3. Resource Abundance and Availability

Abundant minerals such as ilmenite and hematite offer better sustainability and economic feasibility than rare or synthetic compounds (Moattari et al., 2025).

4.4. Cost and Processing Requirements

Low-cost materials that require minimal pre-treatment (e.g., simple grinding or acid washing) are favorable for large-scale use. Energy-intensive synthesis or doping steps reduce sustainability.

4.5. Environmental Sustainability and Toxicity

Environmentally benign minerals with minimal leaching potential are preferred. Materials containing toxic elements such as Cd or Pb are unsuitable for green applications (Gusain et al., 2020).

4.6. Stability and Reusability

A viable photocatalyst must maintain efficiency after multiple cycles without structural degradation. Stable minerals like ilmenite and rutile demonstrate consistent activity over 3–5 cycles (Moattari et al., 2025).

5. Comparison of Parameter Values for Natural Minerals

Table 5.1 shows the comparison of photocatalytic parameters among ilmenite, hematite, and natural rutile.

Table 5.1 Comparison of photocatalytic parameters

Parameter	Ilmenite (FeTiO ₃)	Hematite (Fe ₂ O ₃)	Natural Rutile (TiO ₂)	Benchmark/Ideal Range	References
Band Gap (eV)	2.5–2.7	2.0–2.2	3.0	1.8–3.0	(Gusain et al., 2020).
Degradation Efficiency (MB, 60–120 min)	80–90%	65–75%	70–85%	>80%	(Gusain et al., 2020).
Rate Constant (k, min ⁻¹)	0.021–0.034	0.012–0.018	0.020–0.025	>0.02	(Moattari et al., 2025).
Resource Abundance	High	Very High	Moderate	High	(Gusain et al., 2020).
Processing Requirement	Low (grinding, washing)	Moderate (calcination)	Moderate	Minimal	(Gusain et al., 2020; Moattari et al., 2025).
Environmental Impact	Low, non-toxic	Low	Very low	Non-toxic	(Gusain et al., 2020).
Stability (cycles)	4–5 cycles	3–4 cycles	5+ cycles	≥4	(Gusain et al., 2020).

6. Multi-Criteria Decision-Making (MCDM) Analysis

Evaluating the suitability of natural minerals as photocatalysts requires a systematic comparison of multiple qualitative and quantitative parameters. Multi-Criteria Decision-Making (MCDM) techniques provide a structured approach for such evaluations. In this study, the Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE) was selected due to its robustness, flexibility, and suitability for environmental material assessment. PROMETHEE allows ranking of alternatives based on pairwise comparisons under several criteria, providing a clear visualization of preferences through positive and negative flow values (Brans et al., 2025). Each criterion was assigned a relative importance weight using expert judgment and literature-based relevance analysis. The final normalized weights are shown in Table 6.1.

Table 6.1 Final normalized weights

Criterion	Symbol	Weight (W _i)	Description
Photocatalytic Activity	C1	0.25	Primary indicator of dye degradation performance
Band Gap and Electronic Structure	C2	0.15	Determines light absorption capability
Resource Abundance	C3	0.15	Ensures sustainable raw material supply
Cost and Processing Requirement	C4	0.15	Reflects economic feasibility and simplicity
Environmental Sustainability	C5	0.15	Indicates ecological safety and leaching potential
Stability and Reusability	C6	0.15	Represents catalyst durability and recyclability

The Visual PROMETHEE software was used to compute preference functions and rank the alternatives: ilmenite (FeTiO₃), hematite (Fe₂O₃), and natural rutile (TiO₂). Preference functions of type V were selected for quantitative criteria such as activity and band gap, while usual preference functions were applied for qualitative sustainability criteria. Input values for each mineral were obtained from literature

data summarized earlier. The analysis generated the positive flow (Φ^+), negative flow (Φ^-), and net flow (Φ) for each alternative, representing overall performance and dominance.

7. Results of PROMETHEE Analysis

The multi-criteria decision-making (MCDM) evaluation was performed using Visual PROMETHEE software to compare the suitability of ilmenite, hematite, and natural rutile as natural photocatalysts for wastewater treatment. Six evaluation criteria were considered, including photocatalytic activity, band gap energy, resource abundance, cost and processing requirement, environmental sustainability, and stability. Each criterion was assigned a specific weight to reflect its relative importance.

The PROMETHEE results presented in Figure 7.1 and Table 7.1 indicate that ilmenite achieved the highest net preference flow value ($\Phi = 0.2500$), followed by hematite ($\Phi = 0.1500$), while natural rutile recorded a negative value ($\Phi = -0.4000$). The positive and negative flow results further demonstrate that ilmenite possesses the strongest dominance over the other minerals, with a high Φ^+ value of 0.4250 and a low Φ^- value of 0.1750. The GAIA plane visualization supports this observation by positioning ilmenite closest to the decision axis, confirming its well-balanced performance across all evaluation parameters.

Ilmenite's superior ranking can be attributed to its efficient photocatalytic activity, moderate band gap energy, high natural abundance, and favorable sustainability characteristics. Hematite ranked second, showing good visible-light activity but slightly lower performance in stability and cost-effectiveness. Natural rutile, although stable, showed the weakest overall performance due to its higher band gap energy and processing cost, leading to the lowest ranking among the three minerals.

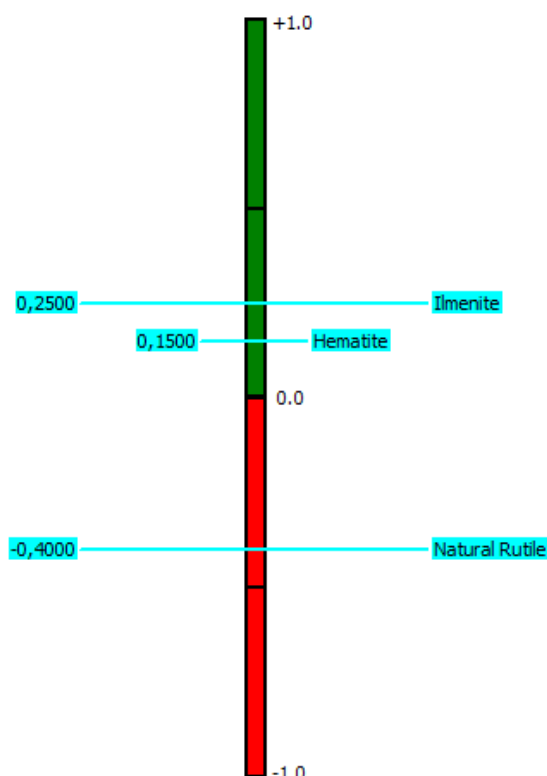


Figure 7.1 Promethea Ranking

Table 7.1 Preference flow value

Rank	Mineral	Φ (Net Flow)	Φ^+ (Positive Flow)	Φ^- (Negative Flow)
1	Ilmenite	0.2500	0.4250	0.1750
2	Hematite	0.1500	0.4000	0.2500
3	Natural Rutile	-0.4000	0.1000	0.5000

8. Conclusion

The MCDM analysis using Visual PROMETHEE confirmed that ilmenite (FeTiO_3) demonstrates the most balanced and effective performance among the evaluated natural minerals for photocatalytic wastewater treatment. Its combination of high photocatalytic efficiency, suitable band gap energy, low processing cost, and favorable environmental characteristics resulted in the highest net preference flow value, indicating superior overall performance. Hematite (Fe_2O_3) ranked second, showing reasonable visible-light photocatalytic activity but moderate stability and cost advantages. Natural rutile (TiO_2) was placed last due to its higher processing cost and limited visible-light response despite its excellent chemical stability. The results highlight ilmenite as a sustainable, low-cost, and efficient natural photocatalyst with strong potential for practical wastewater treatment applications, and the use of the PROMETHEE method provided a reliable and transparent approach for integrating technical, economic, and environmental parameters in material selection.

References

- Ameta, R. and Ameta, S.C., 2016. Photocatalysis: Principles and Applications. CRC Press.
- Andreozzi, R., Caprio, V., Insola, A. and Marotta, R., 1999. Advanced oxidation processes (AOP) for water purification and recovery. *Catalysis Today*, 53(1), pp.51–59.
- Barzagan, A., 2022. Photocatalytic Water and Wastewater Treatment. IWA Publishing.
- Brans, J.P. and De Smet, Y., 2005. PROMETHEE methods. In *Multiple Criteria Decision Analysis: State of the Art Surveys* (pp. 187–219). New York, NY: Springer.
- Gusain, R., Kumar, N. and Ray, S.S., 2020. Factors influencing the photocatalytic activity of photocatalysts in wastewater treatment. In *Photocatalysts in Advanced Oxidation Processes for Wastewater Treatment* (pp. 229–270).
- Guo, J., Zhou, Y., Yu, M., Liang, H. and Niu, J., 2022. Construction of Fe²⁺/Fe³⁺ cycle system at dual-defective carbon nitride interfaces for photogenerated electron utilization. *Separation and Purification Technology*, 285, p.120357.
- Hanafi, M.F. and Sapawe, N., 2020. A review on the current techniques and technologies of organic pollutants removal from water/wastewater. *Materials Today: Proceedings*, 31, pp.A158–A165.
- Ijaz, M. and Zafar, M., 2021. Titanium dioxide nanostructures as efficient photocatalyst: Progress, challenges and perspective. *International Journal of Energy Research*, 45(3), pp.3569–3589.
- Li, Y., Xu, X., Li, Y., Ding, C., Wu, J., Lu, A., Ding, H., Qin, S. and Wang, C., 2018. Absolute band structure determination on naturally occurring rutile with complex chemistry: Implications for mineral photocatalysis on both Earth and Mars. *Applied Surface Science*, 439, pp.660–671.
- Liu, H., Wang, C. and Wang, G., 2020. Photocatalytic advanced oxidation processes for water treatment: recent advances and perspective. *Chemistry – An Asian Journal*, 15(20), pp.3239–3253.
- Mei, J., Gao, X., Zou, J. and Pang, F., 2023. Research on photocatalytic wastewater treatment reactors: design, optimization, and evaluation criteria. *Catalysts*, 13(6), p.974.
- Mishra, A., Verma, V., Khan, A., Kumar, D., Khan, T.S., Amoli, V. and Sinha, A.K., 2023. Waste ilmenite sludge-derived low-cost mesoporous Fe-doped TiO₂: A versatile photocatalyst for enhanced visible light photocatalysis without a cocatalyst. *Journal of Environmental Chemical Engineering*, 11(5), p.110319.
- Moattari, R.M. and Mahinroosta, M., 2025. Magnetic Hematite (α -Fe₂O₃) Photocatalyst in Wastewater Treatment. In *Metal Oxide Based Nanophotocatalyst for Wastewater Purification* (pp. 193–230). Singapore: Springer Nature Singapore.
- Ngulube, K.F., Abdelhaleem, A., Osman, A.I., Peng, L. and Nasr, M., 2024. Advancing sustainable water treatment strategies: harnessing magnetite-based photocatalysts and techno-economic analysis for enhanced wastewater management in the context of SDGs. *Environmental Science and Pollution Research*, pp.1–37.
- Periyasamy, A.P., 2024. Recent advances in the remediation of textile-dye-containing wastewater: prioritizing human health and sustainable wastewater treatment. *Sustainability*, 16(2), p.495.
- Qi, Y., Zhao, S., Shen, Y., Jiang, X., Lv, H., Han, C., Liu, W. and Zhao, Q., 2024. A critical review of clay mineral-based photocatalysts for wastewater treatment. *Catalysts*, 14(9), p.575.
- Racovita, A.D., 2022. Titanium dioxide: structure, impact, and toxicity. *International Journal of Environmental Research and Public Health*, 19(9), p.5681.
- Saremi-Yarahmadi, S., 2010. Preparation and performance of nanostructured iron oxide thin films for solar hydrogen generation (Doctoral dissertation, Loughborough University).
- Shareef, S. and Mushtaq, A., 2023. Wastewater treatment by photocatalysis: approaches, mechanisms, applications, and challenges. *International Journal of Chemical and Biochemical Sciences*, 24, pp.278–286.
- Subasinghe, C.S., Ratnayake, A.S., Roser, B., Sudesh, M., Wijewardhana, D.U., Attanayake, N. and Pitawala, J., 2022. Global distribution, genesis, exploitation, applications, production, and demand of industrial heavy minerals. *Arabian Journal of Geosciences*, 15(20), p.1616.
- Tchounwou, P.B., Centeno, J.A. and Patlolla, A.K., 2004. Arsenic toxicity, mutagenesis, and carcinogenesis: a health risk assessment and management approach. *Molecular and Cellular Biochemistry*, 255(1), pp.47–55.

- Usgodaarachchi, L., Thambiliyagodage, C., Wijsekera, R., Vigneswaran, S. and Kandanapitiye, M., 2022. Fabrication of TiO₂ spheres and a visible light active α -Fe₂O₃/TiO₂-rutile/TiO₂-anatase heterogeneous photocatalyst from natural ilmenite. *ACS Omega*, 7(31), pp.27617–27637.
- Wan, H., Hu, L., Liu, X., Zhang, Y., Chen, G., Zhang, N. and Ma, R., 2023. Advanced hematite nanomaterials for newly emerging applications. *Chemical Science*, 14(11), pp.2776–2798.
- Žerjav, G., Žižek, K., Zavašnik, J. and Pintar, A., 2022. Brookite vs. rutile vs. anatase: What's behind their various photocatalytic activities?. *Journal of Environmental Chemical Engineering*, 10(3), p.10

ICRES26_057

**AN EXPLAINABLE AI-BASED DECISION SUPPORT FRAMEWORK FOR
DETECTING AND OPTIMIZING ENERGY RESOURCE INEFFICIENCIES IN
COMMERCIAL BUILDINGS****M. Shanuga^{1*}, C. Roshan¹, A.S.S.Amath¹, J.D.T.Erandi²**¹*Department of Computing & Information Systems, Faculty of Computing, Sabaragamuwa University of Sri Lanka, Belihuloya, Sri Lanka.*²*Department of Data Science, Faculty of Computing, Sabaragamuwa University of Sri Lanka, Belihuloya, Sri Lanka***Correspondence E-mail: mshanuga2000@gmail.com, TP: +94773725675*

Abstract: The construction industry is the highest energy consumer and the largest emitter of carbon, so the enhancement of the energy efficiency of buildings is the core of sustainability and climate mitigation policies. Though machine learning (ML) models have made the process of building energy forecasting more accurate, little research has combined predictive modelling with organized inefficiency identification and explainable diagnostics for governance-related use. The proposed study will focus on an explainable artificial intelligence (XAI)-supported decision-support system for identifying and optimizing energy resource-related inefficiencies in commercial buildings. With the help of the ASHRAE Great Energy Predictor III dataset, a regression model based on Random Forest was created to predict anticipated energy consumption. A new Energy Resource Inefficiency Index (ERI) was presented to measure the differences between the actual and predicted consumption. Buildings having ERI values that are above 0.3 were considered highly inefficient. Both the global and inefficient-building level analysis using SHAP (SHapley Additive exPlanations) was done to explain the drivers of structural and seasonal inefficiency. The Random Forest model had an MAE of 1809 and was better than the Linear Regression baseline. There were about 10% of observations with serious inefficiency. Findings indicate that building size and seasonal factors have a leading effect, with increased seasonal effects in inefficient cases. The framework takes the traditional forecasting methods a step further by incorporating forecasting, quantifying inefficiency, interpretability, and decisions guided by sustainability. The suggested methodology will offer a scalable energy governance tool and specific optimization of the commercial building management system.

Keywords: Explainable AI; Energy Efficiency; Random Forest; Resource Optimization; SHAP; Sustainability

1. Introduction

The building industry is the primary source of final energy use (around 36% of the world) and almost 37% of the carbon emissions related to energy use, thus it is one of the most critical areas where climate-saving measures should be taken (IEA, 2023). The commercial buildings, such as the office complex, retail center, healthcare institution, and educational facility, constitute a significant share of such demand because of the constant occupancy, sophisticated HVACs, lighting systems, and equipment-centered operation. Commercial facilities also tend to have heterogeneous patterns of energy consumption, unlike residential buildings, since they may have different operating periods, climate variations, and function demands. Consequently, the energy performance of commercial buildings is not only a technical challenge, but also an important sustainability opportunity. The consumption of energy in this type of building depends on the combination of several factors, such as the building structure (e.g., square footage, construction material, insulation measures), environmental factors (e.g., temperature, humidity), occupancy (e.g., how people use the building), and operational factors (e.g., equipment scheduling, HVAC control strategies) (Kavousian et al., 2013). The nonlinear and multidimensional relationships between these factors complicate it naturally to model them correctly and to evaluate them diagnostically. These nonlinear relationships are not well represented by the traditional deterministic modelling techniques. It is generally accepted that building energy efficiency is one of the least expensive and most scalable solutions to climate change mitigation (IPCC, 2022). Retrofitting, smart monitoring, and optimization of operations are some of the policy frameworks and national energy strategies that are focused on ensuring a decrease in the intensity of carbon in the built environment. Nonetheless, traditional energy audits are still relatively periodic, manual, and reactive. They have the usual use of performance evaluation that is based on static performance instead of the application of constant performance diagnostics. This severely restricts their capability to identify dynamic inefficiencies, which occur as a result of the change of season, misalignment of operations or failure of the system with time. The availability of high-resolution energy data has greatly become accessible with the proliferation of smart meters, Internet-of-Things (IoT) devices, and digital building management systems. This digital revolution has provided the possibilities of data-oriented solutions that can monitor the data constantly and analyze it in real time (Ahmad et al., 2020). ML models have been shown to be more successful in modelling high-dimensional and nonlinear energy data than the conventional regression techniques (Zhao and Magouelles, 2012). Random Forest algorithms, represented by Breiman (2001), are among these models, and one of the most effective because they have an ensemble learning structure that minimizes overfitting and enhances generalization over heterogeneous datasets. Temporal dependencies of energy data are also captured using deep learning (Wei et al., 2018). Recent works are implementing machine learning and explainable artificial intelligence-based approaches to enhance building energy analytics and sustainability-oriented decision making more and more (Ahmad et al., 2020; Molnar, 2022; IEA, 2023). In spite of these developments, most studies that are based on ML are still aimed at minimizing forecasting error, also in terms of RMSE, MAE, and R^2 . Although these measures are predictive performance measures, they do not directly translate into actionable inefficiency diagnostics. Higher predictive accuracy does not necessarily determine whether a building is efficiently performing or it is a waste of energy compared to the expected performance. Ideally, energy managers and policymakers need interpretable meters to detect patterns of excessive consumption, identify priority areas for building interventions, and facilitate specific strategies to optimize energy consumption. Moreover, most developed ML models are black boxes, which restricts their interpretability and transparency. Interpretability is not optional in the context of sustainability governance. To levy trust and operationalize the recommendations of a model, a decision-maker needs to know why a particular model yields a particular output. Methods of explainable artificial intelligence (XAI) have thus become the topic of growing interest. The attribution of model predictions to feature contributions is a theoretically motivated approach to explaining the predictions of a model based on cooperative game theory (SHAP SHapley Additive exPlanations), created by Lundberg and Lee (2017). SHAP improves transparency by taking a quantification on the contribution of the input variable to the final prediction. Nevertheless, in spite of the fact that SHAP has been used in energy forecasting research, its incorporation with well-structured inefficiency measurement has not been done to a large extent. Many applications learn global feature importance, but not in a systematic analysis of feature behaviour in inefficient subsets of the building. As a result,

there is still a dire need to bridge the gap between predictive analytics, interpretability mechanisms, and sustainability-oriented decision support. This paper will cover this research gap by suggesting an integrated framework that integrates: The forecasting of building energy consumption, an energy resource inefficiency Index (ERI) based on deviation to measure the wasteful use of energy, Explainability of both global and inefficient-building subsets in comparative SHAP, and Sustainability-driven governance knowledge to focus on optimization. This study goes beyond traditional forecasting by infusing a predictive, quantitative, and interpretive analysis into a single analytical model to achieve diagnostic sustainability analytics. The key contribution is that it converts the predictive outputs into actionable inefficiency intelligence that can support the energy governance, operational optimization, and climate mitigation strategies in the commercial building systems.

2. Literature Review

2.1 Data-Driven Energy Forecasting

The shift from physics-based to data-driven modelling has greatly changed building energy analytics over the last 20 years. Initial models of building energy were based mainly on deterministic simulation and linear statistical methods. Conventional statistical models, such as linear regression and the autoregressive model, were commonly used because they are simple and easy to interpret. Nevertheless, the methods are poor at entrapping nonlinear relationships and complicated interactions among environmental, structural, and operational variables (Dong et al., 2005). The energy use of commercial buildings is affected by several interacting factors that include weather conditions, occupancy patterns, and equipment operation, which tend to be non-linear and time-varying. Machine learning (ML) systems have become popular to overcome all these constraints. One of the initial nonlinear models used in building energy prediction was Support Vector Machines (SVM) (Dong et al., 2005). Then, the ensemble learning algorithms like the Random Forest and Gradient Boosting adopted better results because of their capability to accommodate high-dimensional data and non-linear interaction (Breiman, 2001). Random Forest models, in particular, are stronger against overfitting by bootstrap aggregation as well as random feature selection, which is why it is well applicable to heterogeneous building data. Temporal energy model. Deep learning methods have been investigated more recently. LSTM networks have demonstrated good performance in sequential dependencies and time-dependent dynamics of energy consumption data (Wei et al., 2018). CNNs are also modified to perform forecasting of energy. Although deep learning models may have better accuracy, they frequently demand large datasets, a significant amount of computing resources, and hyperparameter optimization. Even with current developments in predictive performance, most data-driven energy forecasting research focuses on error minimization metrics like RMSE, MAE and R². According to Ahmad et al. (2020) the research on energy analytics needs to be shifted towards operational intelligence and not on the accuracy of forecasting. Predictive accuracy is not necessarily used to determine patterns of inefficiency and give recommendations to be taken. A building can have been a true forecast of usage and still be inefficient compared to the best practices or optimized baseline. Furthermore, most ML models are also black-box systems, which are not very interpretable. This is not very transparent, limiting their use in policy and governance settings, where they need accountability and explainability. As a result, a new requirement is the need to combine predictive modelling with diagnostic and interpretive mechanisms, with the ability to discover drivers of inefficiency as opposed to only predicting consumption.

2.2 Explainable Artificial Intelligence in Energy Systems

The growing sophistication of machine learning models has given rise to the rising worry of transparency and trustworthiness. The explainable Artificial Intelligence (XAI) has thus become a new essential field of research with the intention of explaining complex models without loss of predictive accuracy. SHAP (SHapley Additive exPlanations) is the most popular method of XAI applications as it is well-theoretically based on cooperative game theory (Lundberg and Lee, 2017). SHAP can be used to assign contribution values to each of the features, which are a representation of their marginal contribution to the model prediction. To contrast with the traditional measures of feature importance, SHAP has both global interpretability and local interpretability, enabling researchers to interpret both the overall influence of features and individual behavior case-by-case. According to Molnar (2022), interpretability is important, especially in the areas of governance and sustainability, where decision-

makers should know the reasoning behind a model generating certain advice. SHAP has been used in the energy industry to explain building energy models, determine the leading drivers of weather, and determine the sensitivity of features (Fang et al., 2019). These applications demonstrate the usefulness of SHAP in unearthing latent nonlinear associations between variables that include temperature, building size, and patterns of the time-of-day. Most SHAP applications in energy research are, however, descriptive and not diagnostic. The studies usually show the global feature significance but fail to systematically examine feature performance in inefficient or anomalous subgroups. Limited literature has been conducted to investigate the differences in the contribution of features between efficient and inefficient buildings. Such subgroup analysis is required to complete the interpretability in terms of its operation. In addition, explainability is not often combined with organized measures of inefficiency. Although SHAP clarifies the reason why a prediction is made, it does not necessarily mean that that prediction was an efficient or an inefficient performance. It is an open research question how the predictive deviation analysis can be bridged to explainable diagnostics.

2.3 Energy Efficiency Governance and Sustainability Decision-Making

One of the most cost-effective methods of greenhouse gas reduction is energy efficiency improvement, which is well-known (IPCC, 2022). Policy tools like energy performance standards, building codes, and retrofit incentives are based on quantitative performance ratings. Nevertheless, the systems of governance tend to miss the ongoing use of data-driven diagnostic instruments that can help in pointing at the presence of clusters of inefficiency, in real-time. The International Energy Agency (IEA, 2023) emphasizes that the next-generation energy management systems cannot be impossible without digitalization and smart monitoring technologies. Analytics would be data-driven, which could be used to aid in proactive maintenance, optimization of demand response, and adaptive operation of the buildings to climate conditions. However, good governance does not need raw data and predictive output but rather interpretable output that can inform decisions on resource allocation. The existing sustainability frameworks are often silo-based. The studies of predictive modelling are the ones that concentrate on accuracy; the policy frameworks are those that are concerned with standards and compliance; and the interpretability studies are those that are concerned with transparency, but not explicitly integrated into governance structures. Few studies have integrated deviation-based inefficiency quantification with explainable AI and sustainability-based prioritization strategies. Specifically, there are not many studies that suggest a formal inefficiency index based on predictive baselines and analyze its drivers with explainable AI. Devoid of such an integration, the sustainability decision-making process is always reactive but not proactive.

2.4 Synthesis and Research Gap

The literature review highlights three critical limitations in existing research that collectively constrain the practical impact of data-driven energy analytics.

First, there is a strong prediction-centric focus in existing studies. The majority of research in building energy analytics prioritizes minimizing forecasting error using metrics such as MAE, RMSE, and R^2 . While these metrics are valuable for assessing model performance, they do not inherently reveal whether a building is operating efficiently relative to its expected baseline. Accurate prediction does not necessarily imply optimal performance. A model may successfully predict high consumption for a large building, yet this prediction alone does not determine whether the building is wasting energy beyond what is structurally justified. Consequently, forecasting-oriented research often stops at performance benchmarking, leaving a gap between prediction and actionable inefficiency diagnostics.

Second, existing research exhibits isolated explainability. Explainable AI techniques such as SHAP are increasingly used to interpret machine learning models by identifying influential features. However, in most applications, SHAP is applied descriptively to analyze global feature importance without explicitly connecting interpretations to operational inefficiency detection. In other words, explainability is used to answer “which features influence predictions?” rather than “which features drive inefficiency?” This distinction is crucial. Without a structured inefficiency metric, explainability remains disconnected from sustainability performance evaluation. There is limited research that

compares feature behavior between efficient and inefficient subpopulations to understand how drivers differ under excessive energy consumption conditions.

Third, there is limited integration with sustainability governance and decision-making frameworks. Energy efficiency policies require tools that can prioritize buildings for intervention, allocate retrofit budgets, and support operational optimization strategies. However, most predictive models are not designed as governance-support systems. They generate predictions but do not provide structured mechanisms for ranking inefficiency severity, identifying high-risk facilities, or translating analytical results into resource allocation insights. The absence of such integration reduces the practical utility of advanced analytics in real-world sustainability planning.

Collectively, these limitations indicate a substantial research gap. What is missing is an integrated analytical framework that moves beyond prediction accuracy and combines modelling, quantification, interpretation, and governance alignment into a unified system. This paper fills this gap by suggesting a coherent predictive modelling and Energy Resource Inefficiency Index (ERI)-quantifying and a SHAP-based interpretable decision-support framework. The ERI maps the residuals of predictions into an organized inefficiency measurement, which allows a systematic discovery of excessive patterns of consumption. The comparative analysis that is done using SHAP would then indicate the structural and seasonal aspects behind these inefficiencies. Relying on the ability to tie predictive analytics to interpretability and align governance, the proposed framework transforms machine learning outputs into a form that creates a sustainable intelligence that can be put into action. This way, this study will help to move the field beyond forecasting-based analytics to more diagnostic and governance-based sustainability analytics to increase the practical significance of explainable AI in commercial building energy management systems.

3. Methodology

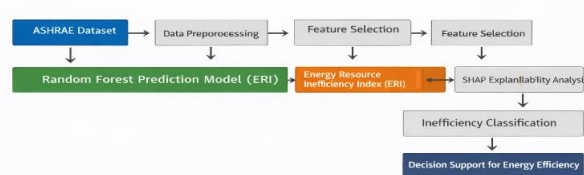


Figure 1: Proposed Methodological Framework

3.1 Dataset Collection

The present research uses the publicly available ASHRAE Great Energy Predictor III dataset (ASHRAE, 2019), originally published as part of an international energy forecasting contest. It is commonly applied to academic studies because of its size, heterogeneity, and practical depiction of patterns of commercial building energy consumption in real-life settings. The data includes hourly meter measurements of over 1,000 commercial structures distributed in various climatic regions. These structures are of different types, such as office buildings, educational facilities, healthcare facilities, retail spaces, and public infrastructure. This heterogeneity makes the dataset more appropriate for the modelling of the generalized energy consumption patterns in commercial environments.

3.1.1 Energy Consumption Data

In this research, the hourly meter of electricity is applied as the initial target variable of energy consumption modelling. Electricity consumption was chosen, whereas other types of meters are present in the dataset because of the uniformity and the available readings in buildings. Not all buildings had detailed thermal energy measurements; hence, electricity consumption is taken as a proxy measure of operational building energy demand, especially HVAC system, lighting, and equipment loads.

3.1.2 Building Metadata

Alongside consumption data, the data will contain building-level metadata such as: square_feet (building size), primary-use(building category), year_built, and site_id (geographic identifier). This

value corresponds to the geographic position of the city being examined. <|human|>site_id (geographic identifier): The value is the geographic location of the city under investigation. The size of the building is also a structural variable that is important to determine the baseline energy demand. The larger the building, the more energy it consumes. Predictive modelling should consider this structural scaling effect so that the high consumption cannot be mistaken for inefficiency. The primary use variable: This variable represents functional diversity (e.g., office, education, lodging), which determines the operational intensity and energy data. Although not every metadata variable was utilized during the initial modelling phase, they apply to interpretability and applications of governance.

3.1.3 Weather Variables

The weather data are also included in the dataset, with respective weather data taken according to the site and time. The important weather variables are: air_temperature, wind_speed, cloud_coverage, and dew_temperature. Among them, the air temperature is one that is the most influential, as it is strongly correlated with the demand for HVAC. Cooling and heating loads caused by temperature vary greatly in the commercial energy consumption of areas with a seasonal climate change (IEA, 2023). By incorporating environmental parameters, the predictive model is further allowed to approximate the anticipated energy baselines as a conditional situation under the condition of climates, instead of using only past averages.

3.1.4 Temporal Features

To extract the temporal dynamics, the information of the timestamp was utilized to extract other features, which included: hour of day, month. These derived variables enable the model to employ the diurnal and seasonal variations in energy consumption. The reason why you need the temporal decomposition is that efficiency patterns can be detected in certain operational hours or seasons.

3.1.5 Characteristics of the Data and Problems

The ASHRAE data set has a number of analysis problems: High dimensionality and heterogeneity- Buildings vary greatly in size, use, and climate conditions. Nonlinearities - Consumption of energy is not directly proportional to the environmental factors. Lack of equal distribution of inefficiency - Inefficient cases are a few observations. Possible missing or noisy values. Real-life data has measurement anomalies. These properties cause the choice of ensemble learning models, including Random Forest, which are resistant to noise, nonlinear interaction, and multicollinearity (Breiman, 2001).

3.1.6 Data Preparation Scope

Since the dataset was large, a representative sample was used in terms of computational considerations, without affecting the statistical distribution. Bad or null meter was eliminated. Moreover, unsettled values that were produced in the calculation of the inefficiency index were filtered to achieve numerical stability.

3.2 Predictive modelling

A Random Forest regression model was applied in order to design an expected baseline of the energy consumption per building observation. Random Forest is an ensemble learning algorithm that was introduced by Breiman (2001) and is used to build many decision trees based on bootstrap aggregation (bagging) and random feature selection. The last prediction is determined as the average of the results of individual trees, thus decreasing variance and overfitting. It is reasonable to select this model because it includes two additional causal variables, namely the payment and the discharge's impact on the firm's financial results and the likelihood of reiteration. <|human|>The reason why this model was selected is that it incorporates two other causal variables, that is, the payment and the effect of the discharge on the financial performance of the firm and the probability of recurrence.

3.2.1 Rationale for Model Selection

The choice of the Random Forest was preconditioned by the following features of the building energy data:

- **Nonlinear Relationships:** The construction of energy consumption is not linear with the environmental factors like temperature. In the case of cooling demand, the demand rises nonlinearly beyond certain temperature limits. Random Forest models can provide such nonlinear interactions without making explicit functional assumptions. The feature space consists of high-dimensional vectors, represented as follows: $\langle \text{human} \rangle$ High-Dimensional Feature Space: The data will be structured into features of structure (e.g., square feet), environmental (e.g., air temperature), and temporal (e.g., hour, month) data. Random Forests models are very good when it comes to multicollinearity and multifaceted interactions between features.
- **Robustness to Noise:** The datasets of real-world buildings have irregularities in measurements and missing values. The effects of outliers and noise are minimized with Ensemble averaging.
- **Interpretability Compatibility:** SHAP-based explainability analysis is fully compatible with random Forest models, which allow one to perform feature attribution without gradient-based approximations.

3.2.2 Baseline Comparison

A Linear Regression model was used to test performance to provide a baseline comparator. The linear regression presupposes the presence of a linear correlation between predictors and the target variable:

$$y = \beta_0 + \sum_{i=1}^n \beta_i x_i + \epsilon \quad (1)$$

But the patterns of energy consumption are hardly always linear. The comparison between the Random Forest and the Linear Regression makes a possibility to determine the advantages of modelling nonlinearities. The Linear Regression model obtained: MAE = 3980. This much greater error indicates that the purely linear modelling is not very effective with heterogeneous building data.

3.2.3 Model Evaluation Metrics

Three standard metrics of regression were used to assess model performance:

Mean Absolute Error (MAE):

$$\text{MAE} = \frac{1}{n} \sum_{i=1}^n |y_i - \hat{y}_i| \quad (2)$$

MAE is used to quantify the mean value of prediction error, and this is less affected by extreme outliers as compared to RMSE. Root Mean Squared Error (RMSE):

Root Mean Squared Error (RMSE):

$$\text{RMSE} = \sqrt{\frac{1}{n} \sum_{i=1}^n (y_i - \hat{y}_i)^2} \quad (3)$$

RMSE is more sensitive to the large errors and gives insight into the stability of some predictions at high consumption levels.

Coefficient of Determination (R^2):

$$R^2 = 1 - \frac{\sum (y_i - \hat{y}_i)^2}{\sum (y_i - \bar{y})^2} \quad (4)$$

3.2.4 Model Performance Results

The random forest model obtained: MAE = 1809, RMSE = 93,679, $R^2 = 0.28$. The Random Forest model decreased absolute error over the baseline Linear Regression (MAE = 3980) by over 50%, which shows the superiority of nonlinear ensemble learning. Though the R^2 value of 0.28 provides moderate variance coverage, this finding must be viewed against the background of constructing energy analytics. The energy consumption of commercial buildings is determined by many unobservable variables, including Occupancy behavior in real time. Equipment scheduling, Maintenance conditions, Efficiencies in control systems.

Kavossian et al. (2013) note that occupant behavior can explain large amounts of differences in electricity consumption. Since the data on occupancy were not directly present in the data, some of the variance is not explained. In turn, this fact makes moderate R^2 values a characteristic of large-scale real-world building datasets. Also, the main aim of this predictive model is not just to increase R^2 alone, but to create the basis of predicted consumption using data, based on which the inefficiency can be measured. In that regard, it is more imperative to have a steadily decreasing error compared to the baseline linear modelling than an extremely high variance explanation. Predictive behavior should be interpreted as an outcome of the current moment; it includes the act of making predictions.

3.2.5 Interpretation of Prediction Behavior

Prediction behavior is to be understood as a product of the present moment; it involves the act of prediction. The Actual vs Predicted scatter plot (Figure X) can be analyzed, and the results are: Good correspondence at medium levels of consumption. Decreased dispersion at extremely high values. This trend implies that although the model is useful in reflecting the overall consumption dynamics, extreme peaks, which are usually caused by abnormal operation conditions, are difficult to forecast. Notably, it is these deviations that allow for analysing the inefficiency that follows later using the index of Energy Resource Inefficiency (ERI). Accordingly, the predictive modelling phase fulfills two functions: Setting of anticipated energy consumption benchmarks. Producing residuals that give information on the inefficiency metric.

4. Results

4.1 Predictive Model Performance

The Random Forest regression model was also created to establish a data-driven benchmark of predicted energy consumption in different structural, environmental, and time conditions. The performance of the model was measured by applying MAE, RMSE, and R^2 .

Table 1: Model Performance Comparison

Model	MAE	RMSE	R^2
Linear Regression	3980	121,500	0.12
Random Forest	1809	93,679	0.28

Random Forest model minimized MAE by over 50% compared to the Linear Regression baseline. This enhancement explains the nonlinear nature of building energy dynamics. Linear regression includes constant marginal effects of predictors, and the Random Forest includes threshold-based and cross-interaction-induced actions. The R^2 of 0.28 implies the model can explain the variation in the energy consumption by about 28%. Although this might be considered moderate, it agrees with the large-scale real-world building datasets that a high level of variability can be generated due to the lack of observability of behavioral and operational (Kavousian et al., 2013). Stochastic variability is added by occupant behaviour, variation in equipment use, and the state of the maintenance, and it is challenging to model without extra sensor information. Notably, the goal of this model is not just to maximize predictive accuracy but produce an effective baseline on which inefficiency can be measured. Baseline stability is what is more important in sustainability analytics than absolute predictive perfection.

4.2 Actual vs Predicted Consumption Dynamics

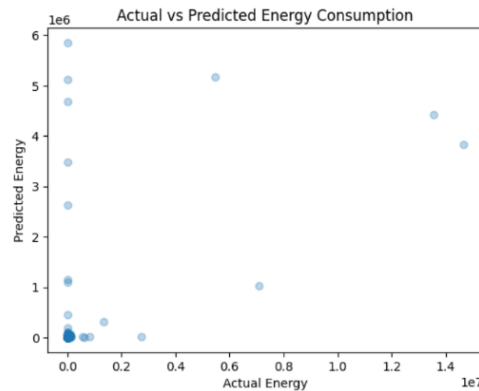


Figure 2: Actual vs Predicted Scatter Plot

The scatter plot shows the correlation between the actual and the predicted energy consumption. A number of key trends can be identified:

- Vigorous clustering in the intermediate energy levels.
- High dispersion at elevated consumption levels.
- Disproportionate prediction behavior at harbors.

The model works well in regular working conditions, though it does not fully model extreme energy spikes. These extreme deviations can be an indication of an abnormal state of operations like: High duration of HVAC running outside the occupancy period. Equipment malfunction Sudden occupancy surges, and system inefficiencies. Importantly, these deviations are not only modelling failures, but they are also possible indicators of inefficiency. However, instead of ignoring residual error as statistical noise, such errors are used to diagnose the study.

4.3 Distribution of Energy Resource Inefficiency

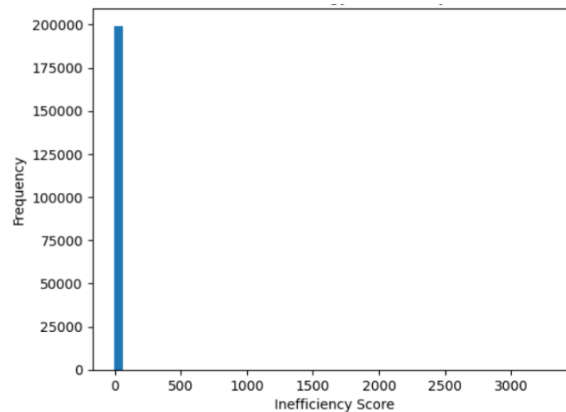


Figure 3: ERI Distribution Histogram

ERI distribution has a high right-skewness. Most observations are concentrated around the value of zero, which could be an indication of consistency between the predictive and actual energy consumption. Nevertheless, the long right tail suggests concentrated excessive cases of consumption.

Table 2: ERI Classification Summary

Metric	Value
ERI Threshold	0.30
Efficient Cases	89.7%
Highly Inefficient Cases	10.3%

Approximately 10.3% of observations exceed the inefficiency threshold. This minority concentration is highly significant from a governance perspective. It suggests that energy waste is not uniformly distributed but concentrated among specific building-period combinations. Such clustering enables targeted intervention strategies rather than system-wide retrofiting.

4.4 Building-Level Inefficiency Ranking

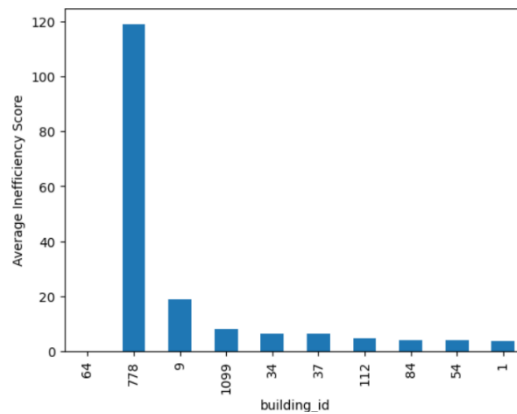


Figure 4: Top 10 inefficient buildings

The ranking analysis determines the buildings that have the greatest average ERI values. Building 778 has an unusual amount of inefficiency when compared to others. The scale of deviation indicates that there is an inefficiency of the system and not a mere chance variation. This prioritization system involves the conversion of predictive modelling into prioritization into action. The energy managers will be able to invest in the best-ranked buildings to bring maximum impact. This kind of prioritization is in line with the principles of sustainability governance, which focus on efficiency in resource allocation.

4.5 Seasonal Amplification Effects

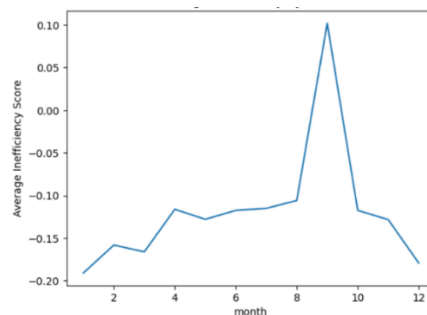


Figure 5: Monthly Inefficiency Trend

The Monthly aggregation of ERI shows that there was a sharp spike in Month 9. This shows seasonal magnification of inefficiency, which was probably fuelled by high cooling demand. Buildings that are used commercially tend to have nonlinear increases in HVAC load when the temperature is high. The spike that was observed indicates that: Cooling systems can be either oversized or improperly calibrated. There can be a lack of thermal insulation. Dynamic schedule It is possible that operational schedules do

not dynamically adapt to temperature variation. This seasonal tendency proves the fact that inefficiency is not a constant state, but climate-dependent. Sustainability plans should then incorporate seasonal adaptation plans.

4.6 Global Feature Contributions (SHAP Analysis)

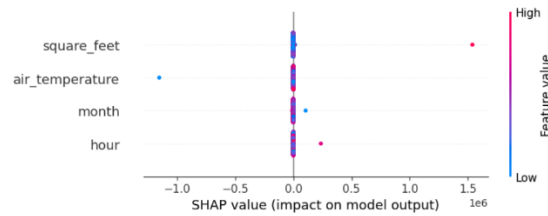


Figure 6: Global SHAP Plot

With the global SHAP summary plot, square feet is the most significant structural predictor, followed by air temperature, and month and hour are the temporal dynamics. The main factors affecting expected baseline energy demand are the size of the building and environmental temperature, which is nonlinear with high values. The SHAP visualization identifies the complicated interactions of features that cannot be seen in linear models, which proves the importance of nonlinear ensemble learning.

4.7 Inefficient-Only SHAP Analysis

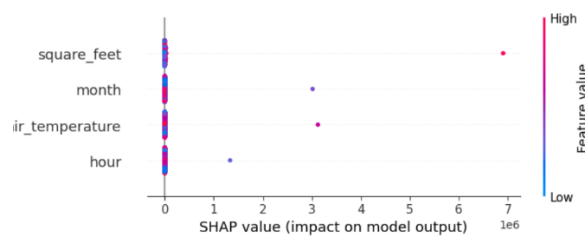


Figure 7: Inefficient SHAP Plot

In the case when SHAP is applied only on the observations with ERI more than 0.3, the contributions of a feature change significantly. Effects seasonal and related to temperature are amplified, and the contribution to dispersion is higher. This shows that the environmental stressors are more sensitive in an inefficient building. Baseline demand is characterized by structural elements, but climate responsiveness leads to a rise in inefficiency. This type of comparative explainability method is an important contribution of the research.

4.8 Classification Performance and Imbalance Analysis

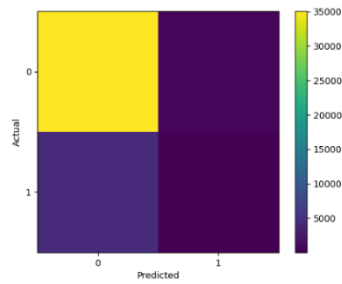


Figure 8: Confusion matrix

Table 3: Classification Metrics

Class	Precision	Recall	F1-score
Efficient	0.89	0.98	0.94
Inefficient	0.06	0.01	0.02
Overall Accuracy	0.88	—	—

Despite a high overall accuracy (0.88), the recall of inefficient cases is low because of the imbalance in classes. This brings out a general problem in sustainability analytics where inefficient events are not frequent but significant. Further research in the future should be done on models that are sensitive to cost, methods of resampling like SMOTE, or anomaly-detecting methods to enhance minority classification.

4.9 Integrated Interpretation

The findings indicate that nonlinear modelling is a dependable energy reference on which deviation-based detection of inefficiency can be done. Inefficiency is stagnated within a limited number (~10%) and is multiplied by seasonal and environmental conditions. The size of the structures determines anticipated demand, whereas the excessive consumption is fuelled by climate responsiveness. It is methodologically difficult to detect rare cases of inefficiency.

4.10 Implications of the Practice and Sustainability

The structure facilitates specific audits of high-ERI buildings, climate-adaptive optimization of HVAC, and seasonal monitoring in terms of ERI. The methodology can be used to support practical sustainability decision-making by integrating prediction, inefficiency indexing, and explainable AI.

5. Discussion

The findings prove that the combination of nonlinear predictive modelling and deviation-based inefficiency quantification offers significant diagnostic information on the performance of commercial buildings in terms of energy. Even though predictive accuracy was at the medium level, the model was able to set a predictable minimum to determine excessive consumption. It was found that inefficiency is concentrated on a small number of cases, and increased by seasonal and environmental influences, according to the ERI distribution. The comparative SHAP analysis also revealed that the structural scale is a determinant of the baseline demand, and climate responsiveness is a determinant of the inefficiency increase. The results indicate the significance of prediction, interpretability, and governance alignment in sustainability analytics. The characteristics of the building envelope including orientation, the ratio of windows to walls, material properties, and the location of the fenestration were not present in the dataset and thus could not be utilized in the predictive model, which is also a limitation of the current study.

6. Conclusion and Future Work

This paper presented an explicable AI-based decision-support system to identify and analyze the energy resource inefficiency of commercial buildings. Combining predictive models based on the Random Forest, a deviation-derived Energy Resource Inefficiency Index (ERI), and comparative SHAP analysis allows the framework to have a long-standing forecasting methodology extended to the diagnostic and governance-oriented sustainability analytics. The findings showed that nonlinear modelling is much better in estimating the baseline than linear regression, and that a percentage of 10 seems to be concentrated inefficiency. Amplification seasonally and temperature sensitivity were found to be the important drivers of superfluous energy consumption, with structural scale being the principal determinant of baseline demand. The comparative explainability analysis showed that inefficient buildings are more sensitive to environmental stressors, which can be used to generate actionable information to be used to perform specific audits and climate-adaptive operational plans. Although the framework has moderately high performance in R^2 and class imbalance issues in inefficient classification, the framework has been effectively used to convert predictive residuals into structured sustainability intelligence. Further studies are advised to include information on occupancy behavior, IoT-based sensors, and cost-sensitive or anomaly-detection algorithms to enhance the detection of minority inefficiency. Furthermore, reinforcement learning and adaptive control techniques can be considered in order to provide the possibility of real-time control of the HVAC system and improve dynamic energy management within the commercial building climate.

Acknowledgement

We are thankful to ASHRAE for making the publicly available dataset to be employed in this study. The respective institutions in which we conducted the research have also been credited in the study.

References

- Ahmad, T., Chen, H., Guo, Y. and Wang, J. (2020) 'A comprehensive overview on the data-driven and large-scale based approaches for forecasting of building energy demand', *Energy and Buildings*, 165, pp. 301–320.
- ASHRAE (2019) ASHRAE Great Energy Predictor III Competition Dataset. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers. Available at: <https://www.kaggle.com/c/ashrae-energy-prediction> (Accessed: 15 February 2026).
- Breiman, L. (2001) 'Random Forests', *Machine Learning*, 45(1), pp. 5–32.
- Chicco, D. and Jurman, G. (2020) 'The advantages of the Matthews correlation coefficient over F1 score and accuracy in binary classification evaluation', *BMC Genomics*, 21(6), pp. 1–13.
- Dong, B., Cao, C. and Lee, S.E. (2005) 'Applying support vector machines to predict building energy consumption in tropical region', *Energy and Buildings*, 37(5), pp. 545–553.
- Fang, T., Lahdelma, R. and Dong, L. (2019) 'An improved feature selection approach based on SHAP for energy consumption modelling', *Applied Energy*, 251, 113345.
- Granderson, J., Lin, G., Piette, M.A. and Ghatikar, G. (2016) 'Building energy information systems: State of the technology and user case studies', *Energy Efficiency*, 9(4), pp. 851–871.
- Hong, T., Chen, Y., Luo, X., Luo, N. and Lee, S.H. (2015) 'Ten questions on urban building energy modelling', *Building and Environment*, 100, pp. 196–205.
- IEA (2023) *Energy Efficiency 2023*. Paris: International Energy Agency. Available at: <https://www.iea.org/reports/energy-efficiency-2023> (Accessed: 15 February 2026).
- IPCC (2022) *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge: Cambridge University Press.
- Kavousian, A., Rajagopal, R. and Fischer, M. (2013) 'Determinants of residential electricity consumption: Using smart meter data to examine the effect of climate, building characteristics, appliance stock, and occupants' behavior', *Energy*, 55, pp. 184–194.
- Lundberg, S.M. and Lee, S.I. (2017) 'A unified approach to interpreting model predictions', *Advances in Neural Information Processing Systems*, 30, pp. 4765–4774.
- Molnar, C. (2022) *Interpretable Machine Learning*. 2nd edn. Available at: <https://christophm.github.io/interpretable-ml-book/> (Accessed: 15 February 2026).
- Sovacool, B.K. (2016) 'How long will it take? Conceptualizing the temporal dynamics of energy transitions', *Energy Research & Social Science*, 13, pp. 202–215.
- United Nations (2015) *Transforming our world: The 2030 Agenda for Sustainable Development*. New York: United Nations.
- Ürge-Vorsatz, D., Cabeza, L.F., Serrano, S., Barreneche, C. and Petrichenko, K. (2015) 'Heating and cooling energy trends and drivers in buildings', *Renewable and Sustainable Energy Reviews*, 41, pp. 85–98.
- Wei, Y., Li, Y., Zhang, X. and Wang, G. (2018) 'A review of data-driven approaches for building energy forecasting', *Renewable and Sustainable Energy Reviews*, 82, pp. 1027–1047.
- Zhao, H.X. and Magoulès, F. (2012) 'A review on the prediction of building energy consumption', *Renewable and Sustainable Energy Reviews*, 16(6), pp. 3586–3592.



ICRES

International Conference on
Resource Efficiency Towards Sustainability

**International Conference on
Resource Efficiency Towards Sustainability**

**CIRCULAR ECONOMY FOR INDUSTRY AND
CLIMATE RESILIENCE**

ICRES26_031

**COST ESTIMATION BARRIERS IN THE ADOPTION OF CIRCULAR ECONOMY
PRACTICES IN THE SRI LANKAN CONSTRUCTION INDUSTRY**

W.G. Pabodha*, K.P.S.P.K. Bandara

*Department of Quantity Surveying, Faculty of Built Environment and Spatial Sciences (FBESS), General Sir
John Kotelawala Defence University, Sri Lanka*

**Correspondence E-mail: 38-bqs-0021@kdu.ac.lk, TP: +94705096494*

Abstract: The construction industry is increasingly encouraged to adopt circular economy practices to mitigate resource depletion and environmental impacts. However, economic constraints continue to limit their practical implementation. These constraints are particularly high in developing countries. This study assesses the cost estimating barriers affecting the adoption of circular economy practices in the Sri Lankan construction industry. The focus is on pricing mechanisms, cost planning practices, procurement-related challenges. A mixed-method research approach integrated a structured questionnaire survey of construction professionals with semi-structured expert interviews. Quantitative data were analysed using Descriptive Statistics and Relative Importance Index (RII) techniques to rank key cost estimating barriers. A Qualitative Thematic Analysis was used to analyse interview data to explore their underlying causes and contextual implications. The findings reveal high initial investment costs, lack of standard pricing mechanisms for circular materials, uncertainty regarding life-cycle cost benefits, limited financial incentives, and rigid lowest-price-based procurement practices are the most critical barriers hindering circular economy adoption. The results further indicate that prevailing cost management and pricing approaches in Sri Lanka prioritize short-term capital cost minimization over long-term value creation. It discourages the circular construction solutions. The study contributes empirical evidence from a developing country context and highlights the pivotal role of quantity surveying practice in facilitating circular economy adoption. Practical implications are provided for improving cost planning methods, pricing frameworks, procurement strategies, and policy support to enhance the economic viability and industry uptake of circular construction practices.

Keywords: Circular Economy; Sustainable Construction; Cost Estimation Barriers; Quantity Surveying; Sri Lanka

1. Introduction

The construction industry is a major contributor to economic growth. But construction is exerting substantial pressure on natural resources through intensive material consumption and waste generation. Globally, construction and demolition activities account for a significant proportion of solid waste and embodied carbon emissions. This highlights that there is urgent need for alternative production and consumption models (Ghisellini et al., 2016; Pomponi and Moncaster, 2017). In this context, the circular economy (CE) has emerged as a systemic concept. Circular Economy principles seek to decouple economic growth from resource depletion. It is achieved through promoting material reuse, recycling, life-cycle optimisation, regenerative design strategies etc.

Within the construction sector, there are numerous CE adoption practices. Key applications are design for disassembly, adaptive reuse, modular construction, closed-loop material flows (Charef et al., 2021). Those CE practices bring recognised long-term environmental as well as economic benefits. But the implementation of CE principles in construction remains limited, particularly in developing countries. Existing studies indicate that economic considerations play a key role in these limitations. Key factors hindering the CE adoption are those related to cost, pricing, and financial risk. They play a critical role in shaping industry adoption behaviors (Häkkinen and Belloni, 2011; Rakhshan et al., 2020).

In Sri Lanka, the construction industry has experienced rapid expansion in infrastructure development and urban growth in recent decades. However, construction practices continue to follow a predominantly linear model. This model is characterized by short-term cost minimization and conventional procurement strategies. There are recent studies have explored the application of CE principles during early project stages in Sri Lanka. But their application is minimum. On the other hand, these investigations have largely focused on environmental and technical aspects rather than economic feasibility (Wijewansa et al., 2021).

The socio-economic and environmental implications of adopting CE practices in Sri Lanka are considerable. Rapid urbanisation and infrastructure expansion have intensified construction waste accumulation and carbon emissions. It further places growing pressure on landfill capacity and urban environmental quality (Wijewansa et al., 2021). Economically, transitioning towards circular construction could reduce dependency on imported raw materials. It is particularly critical given Sri Lanka's recent foreign exchange crisis. That severely disrupted material supply chains and escalated project costs (Central Bank of Sri Lanka, 2022). Furthermore, CE adoption could stimulate local employment in material recovery and green construction sectors. As a result, possibility to generate long-term savings through reduced waste disposal costs and improved asset lifecycle performance (Charef et al., 2021). However, empirical evidence is limited on how construction cost estimation mechanisms constrain CE adoption in the Sri Lankan construction industry.

Cost estimations and procurement decisions are crucial to smooth construction project delivery. They can be considered as the foundation of the whole construction process. But particularly in competitive markets as in Sri Lanka, lowest price tendering dominates. There are many reasons behind it such as unstable economies and high inflation etc. On the other hand, according to global as well as local studies, circular construction practices often involve higher initial costs, pricing uncertainty, lack of established cost benchmarks etc. These are the reasons which discourages clients and contractors from deviating from conventional methods (Jaillon and Poon, 2014; Charef *et al.*, 2021). This study addresses this critical research gap by systematically examining construction cost estimating barriers to CE adoption in Sri Lanka. The study aims to identify, rank, and analyse these barriers while offering practical insights for quantity surveying practice, procurement systems as well as policy development.

2. Literature Review

2.1 Circular Economy in the Construction Industry

The circular economy is defined as an economic system designed to retain the value of products, materials, and resources for as long as possible while minimising waste generation (Ellen MacArthur Foundation, 2015). In construction, CE principles can be applied in numerous ways. For instance, there

are strategies such as material reuse, recycling of construction and demolition waste, design for adaptability, and prefabrication etc. (Ghisellini *et al.*, 2018). Compared to manufacturing and other industries, CE implementation in construction is more complex. The key reason behind is project-based production. Every construction project is a unique work itself with unique contributing factors. Furthermore, construction is a complex process itself with fragmented supply chains and long asset life cycles (Pomponi and Moncaster, 2017).

Recycling has gained traction globally and considerable implementation can be seen globally as well as locally. But higher order CE strategies such as reuse and design for deconstruction remain under-utilised. The reason is due to technical, organisational, and economic constraints (Charef *et al.*, 2021). It needs several initial steps to be taken in planning of adopting these strategies. Several studies emphasise that economic feasibility is a prerequisite for mainstream CE adoption. It is particularly high in cost sensitive construction markets in developing countries such as Sri Lanka.

2.2 Cost Estimating Challenges in Circular Construction

Economic barriers are consistently identified as the most influential factors to CE adoption in construction. High initial investment costs associated with circular materials is one of the key barriers. Construction usually involves with considerable high monetary value investments. Therefore, budgeting is a key constraint as clients are always in need of reducing the budget as much as possible. specialised design processes and alternative construction methods are frequently cited in the literature as other barriers which also takes more additional time and cost (Häkkinen and Belloni, 2011; Jaillon and Poon, 2014). These costs are often incurred during early project stages. But economic benefits of these CE practices are realised over longer operational periods. It creates a misalignment with traditional cost evaluation practices.

Pricing uncertainty further constrains CE adoption. Reused and recycled materials often lack standardised pricing mechanisms. It is making cost estimation and risk allocation difficult for quantity surveyors and contractors specially in the initial cost estimating process (Chileshe *et al.*, 2015; Rakhshan *et al.*, 2020). In addition, virgin materials frequently remain cheaper due to established supply chains. On the other hand, there is an absence of environmental cost internalisation. It is reducing the market competitiveness of circular alternatives (Charef *et al.*, 2021).

2.3 Evidence from Developing Country Contexts

Studies conducted in developing economies reveal that economic barriers to CE adoption are exacerbated by number of reasons. Some of them are, limited policy support, insufficient financial incentives, low market maturity etc. (Hosseini *et al.*, 2015; Wijewansa *et al.*, 2021). Traditional procurement systems prioritising lowest initial cost discourage innovation. Therefore, stakeholders tend to avoid taking a risk by initiating with different but sustainable practices. Further they reinforce linear construction practices. Moreover, the lack of life-cycle cost data and performance benchmarks undermines confidence in the economic viability of CE practices.

2.4 Synthesis of Cost and Pricing Barriers

The literature identifies recurring construction cost estimating barriers including high upfront investment, lack of standard pricing structures, uncertainty regarding life-cycle cost benefits, limited financial incentives, risk-averse procurement practices and many more. These barriers collectively shape stakeholder resistance to CE adoption. This happens particularly in contexts where short-term cost efficiency dominates decision-making.

2.5 Research Gap

Existing studies have extensively examined technical, organisational, policy related barriers to circular economy implementation in construction specifically in Sri Lankan context. But empirical investigations that focus specifically on cost estimating barriers remain limited. It is limited not only in Sri Lankan context but particularly within developing country contexts (Charef *et al.*, 2021; Rakhshan *et al.*, 2020). Furthermore, there is a notable lack of context-specific quantitative ranking and qualitative

explanation of how pricing mechanisms, cost planning practices, procurement systems influence circular economy adoption in the Sri Lankan construction industry. These are highlighting a critical research gap that this study seeks to address (Häkkinen and Belloni, 2011; Wijewansa et al., 2021).

3. Research Methodology

This study adopted a mixed-method research approach. It is aimed to comprehensively investigate cost and pricing barriers to CE adoption in the Sri Lankan construction industry. An initial literature review was conducted to identify potential cost estimation and pricing related barriers relevant to circular construction. The overall focus was initially on global context and then focused in depth towards developing economies. The reason is to get insights from the similar contexts.

A structured questionnaire survey was then used to collect quantitative data from construction professionals in Sri Lankan construction industry. Population was Quantity Surveyors, Estimators Costing related professionals, Client and Contractor representative professionals and consultants in Sri Lankan construction industry. The reason is they are involved in the and have exposure to the costing aspect of a construction project. A Google Form structured questionnaire was distributed to 80 construction professionals using a stratified sampling strategy. Targeted individuals with direct involvement in construction cost management activities. Stratified sampling was adopted to ensure that selected respondents possessed relevant professional knowledge and practical experience in cost estimating and procurement within the Sri Lankan construction industry. A total of 60 complete and usable responses were received giving a response rate of 75%. Respondents evaluated identified barriers from literature using a five-point Likert scale. Mean Score and Relative Importance Index (RII) methods were applied (Eq. (01)) to rank the barriers in Sri Lankan context according to their perceived significance.

$$RII = \Sigma W / (A \times N) \quad (1)$$

Where W represents the weighting assigned by respondents, A is the highest possible weight, N is the total number of responses.

To gather qualitative data and to validate quantitative analysis results from the questionnaire, 10 semi structured interviews conducted. Population was construction cost estimating experts and senior quantity surveyors who had more than 15 years of experience in the industry. Expert interviews were analysed thematically to explain underlying causes and contextual factors manually. Then, integrated with the quantitative results to provide contextual explanations.

4. Results and Analysis

4.1 Quantitative Analysis of Cost and Pricing Barriers

Quantitative data obtained from the questionnaire survey were analysed using Mean Score and Relative Importance Index (RII) methods. The aim was to assess the relative severity of cost estimating barriers affecting CE adoption. These techniques are widely used in construction management research to rank factors based on stakeholder perception. Further it can be used to facilitate comparative analysis.

Respondents evaluated a set costing and pricing barriers identified from the literature using a five-point Likert scale. Mean Score analysis provided an initial indication of perceived severity. Calculated RII values were used to rank the barriers in descending order of importance.

Table 1: Ranked cost and pricing barriers based on the combined Mean Score and RII results

Rank	Barrier	Mean Score	RII
1	High initial investment cost	4.41	0.88
2	Lack of standard pricing for circular materials	4.28	0.86
3	Uncertainty in life-cycle cost benefits	4.15	0.83
4	Limited financial incentives and subsidies	4.02	0.80
5	Higher cost of recycled/reused materials	3.94	0.79
6	Risk-averse procurement practices	3.88	0.78
7	Lack of cost data and benchmarks	3.76	0.75

The results indicated that high initial investment cost emerged as the most critical barrier. It is followed by lack of standard pricing mechanisms for circular materials and uncertainty regarding life cycle cost benefits. These findings suggest that economic risk perception strongly influences decision-making in the Sri Lankan construction industry.

4.2 Thematic Analysis of Qualitative Data

Qualitative data obtained from expert interviews were analysed thematically to explore the underlying causes of the identified cost and pricing barriers. The qualitative importance scores (out of 10) were derived through thematic intensity assessment. It is based on the frequency of expert references.

Table 2: Thematic Evaluation of Cost and Pricing Barriers Based on Qualitative Expert Interviews

Major Theme	Qualitative Importance Score (Out of 10)	Key Sub-Factors Identified from Interviews
Market and Pricing Structure Limitations	10/10	<ul style="list-style-type: none"> • Absence of an established market for circular materials • Limited number of reliable suppliers • Inconsistent quality of recycled and reused materials • Lack of price transparency across suppliers • Difficulty in cost prediction and risk allocation • Reluctance of clients and designers to specify circular materials due to perceived financial risk
Procurement and Contractual Practices	8/10	<ul style="list-style-type: none"> • Predominance of lowest-price tendering systems • Emphasis on initial capital cost rather than life-cycle value • Limited use of value-based or performance-based procurement • Absence of contractual mechanisms for cost recovery of circular investments • Lack of flexibility in contracts to accommodate innovative materials and methods
Cost Planning and Professional Capacity Constraints	7/10	<ul style="list-style-type: none"> • Lack of cost databases and benchmarks for circular materials • Limited expertise in life-cycle cost (LCC) analysis • Absence of standard estimating tools for circular construction • Conservative pricing approaches by quantity surveyors • Reliance on conventional cost norms and historical rates
Regulatory and Institutional Gaps	7/10	<ul style="list-style-type: none"> • Absence of national pricing guidelines for circular construction • Limited government incentives, subsidies, or tax benefits • Weak policy enforcement supporting CE adoption • Fragmented institutional responsibilities related to sustainability
Information Asymmetry and Data Uncertainty	6/10	<ul style="list-style-type: none"> • Lack of reliable historical performance data • Uncertainty regarding durability and long-term performance • Limited documentation of successful local case studies • Inadequate dissemination of cost and performance information
External Economic and Market Conditions	6/10	<ul style="list-style-type: none"> • Inflationary pressures and price volatility • Exchange rate fluctuations affecting imported circular technologies • Higher sensitivity of circular materials to economic instability • Increased financial risk perception under uncertain macro-economic conditions

Experts highlighted the absence of an established market for circular construction materials in Sri Lanka. There is a limited supplier availability for circular materials in Sri Lankan context. On the other hand, inconsistent quality causes reduced demand for specific materials and suppliers. Further, lack of price transparency was identified as key contributors to pricing uncertainty. As almost all construction project is strict with budget this is identified as a crucial factor. This market immaturity discourages contractors from adopting circular alternatives due to difficulties in cost prediction and risk allocation. Furthermore, most clients as well as design professionals do not tend to select circular materials due to these discussed barriers mainly to avoid the risk.

Traditional procurement systems particularly lowest price tendering was identified as a major constraint. Experts noted that such systems prioritise initial cost over long-term value. Most of the clients prioritize low cost tenders compared to others. It is making it difficult to justify circular solutions that offer life-cycle benefits but higher upfront costs. Contractual arrangements rarely accommodate cost recovery for circular investments is another identified key issue.

Interview findings revealed limitations in professional capacity to evaluate and price circular construction options. Quantity surveyors often lack access to cost databases, benchmarks, tools for life-cycle cost analysis specifically involved with circular materials. It is leading to conservative pricing approaches that favour conventional materials and methods.

In addition to the three dominant themes discussed above, the thematic analysis also revealed several contextual factors that further intensify estimating barriers to circular economy (CE) adoption. Experts pointed to regulatory and institutional gaps. They include the absence of clear national guidelines, incentives, standardized cost frameworks etc. for circular construction. This is which results in fragmented and ad hoc pricing practices. The lack of government-led price controls, tax incentives, subsidies etc. for reused and recycled materials was highlighted as another factor. It is making circular options financially less attractive compared to conventional materials.

Moreover, information asymmetry and data limitations emerged as another important aspect. Experts emphasized factors such as the scarcity of reliable historical cost data, performance records, risk profiles for circular materials etc. They can increase uncertainty during tendering and budgeting stages. On the other hand, there is limited client awareness and they have risk-averse attitudes. Clients tend to prioritize cost certainty and programme reliability over long-term economic benefits.

Macro-economic instability is another identified barrier. It is including fluctuating exchange rates and inflationary pressures in Sri Lanka. It was identified as an external factor that disproportionately affecting circular materials. Most of the circular materials rely on specialized processing or imported technologies. Therefore, professionals are reinforcing conservative cost decisions. These additional factors interact with market and create a systemic environment that constrains the effective integration of circular economic practices.

4.3 Synthesis of Quantitative and Qualitative Findings

The integration of quantitative and qualitative findings provides a comprehensive understanding of the cost and pricing barriers to CE adoption in the Sri Lankan construction industry.

The quantitative analysis established most critical barriers which are, high initial investment cost, lack of standard pricing mechanisms, uncertainty in life-cycle cost benefits. That indicates that stakeholders' decisions are predominantly driven by short-term cost considerations as well as perceived financial risk. These statistically ranked barriers are strongly supported by the qualitative insights. Those explain why such perceptions persist. Expert interviews revealed that market immaturity, limited supplier availability, poor price transparency etc. underpin the absence of standard pricing and elevate upfront costs. On the other hand, uncertainty in life-cycle cost benefits identified in the survey is closely linked to deficiencies in cost planning capacity, lack of reliable cost databases, limited application of life-cycle costing tools in practice.

Furthermore, risk-averse procurement systems which are particularly lowest-price tendering and they provide a structural explanation for why high initial costs and long-term value considerations are systematically deprioritized. The qualitative findings also extend the quantitative results by highlighting contextual and institutional factors. Examples are such as weak regulatory support, inadequate incentives, information asymmetry, macro-economic instability etc. They are intensifying the ranked barriers identified through RII analysis.

5. Discussion

The findings of this study reinforce global research identifying economic barriers as the most significant constraints to CE adoption in construction (Häkkinen and Belloni, 2011; Charef *et al.*, 2021). However, the Sri Lankan context reveals a stronger influence of pricing uncertainty and procurement rigidity compared to developed economies. The reason is policy incentives and mature secondary material markets partially offset cost concerns.

The prominence of high initial costs aligns with previous studies indicating that circular construction requires early-stage investment. It conflicts with traditional cost-minimisation objectives (Jaillon and Poon, 2014). Moreover, the lack of standard pricing frameworks mirrors findings from other developing economies. The reason is limited market maturity amplifies financial risk perception (Rakhshan *et al.*, 2020).

The integration of qualitative findings demonstrates that cost barriers are not solely financial in nature. They are embedded within institutional and professional practices. The continued reliance on lowest-price tendering and conventional BOQ structures restricts the ability of quantity surveyors to incorporate life-cycle value into pricing decisions. It is a critical problem. This supports previous assertions that CE adoption requires systemic changes in cost management and procurement frameworks rather than isolated technical interventions (Pomponi and Moncaster, 2017).

Comparative evidence from similar developing economies reinforces these findings. Studies from South Africa and Malaysia identify lowest-price tendering, pricing uncertainty, limited government incentives etc as dominant barriers closely mirroring the Sri Lankan context (Chileshe *et al.*, 2015; Hosseini *et al.*, 2015). However, Sri Lanka's situation is further compounded by recent macroeconomic instability. It further includes currency depreciation and inflation which disproportionately affected circular materials dependent on imported technologies (Central Bank of Sri Lanka, 2022). Unlike India and Bangladesh, where green procurement policies have begun partially offsetting economic barriers, Sri Lanka lacks equivalent policy frameworks. It amplifies the financial risks of CE adoption (Rakhshan *et al.*, 2020).

The findings highlight that market-driven mechanisms alone are insufficient to overcome these barriers. Targeted policy intervention is required. They include national pricing guidelines for circular materials, financial incentives such as green tax relief and procurement subsidies, mandatory life-cycle costing requirements in public sector procurement etc. (Charef *et al.*, 2021). In the long term, such measures could reduce material import expenditure, lower waste disposal costs further. They can improve asset lifecycle value outcomes demonstrated in economies such as the Netherlands and Denmark following sustained CE policy implementation (Pomponi and Moncaster, 2017). For Sri Lanka, even incremental policy steps could generate significant efficiency gains mainly within the public infrastructure sector.

Overall, the synthesis demonstrates strong convergence between both data strands. It is further confirming that cost and pricing barriers are not isolated financial issues. It is confirming they are embedded within broader market and institutional systems. Further they are collectively constraining the adoption of circular economy practices in Sri Lankan construction projects.

6. Recommendations

To address the identified cost and pricing barriers targeted interventions are required at different levels. They have to focus on professional, organisational and policy levels as well. Firstly, cost planning practices should be expanded beyond initial construction costs to incorporate life-cycle costing approaches. Even though the concept is well known by Sri Lankan Quantity Surveyors, the applicability is limited. Quantity surveyors should integrate long-term operational, maintenance, end-of-life considerations into BOQ preparation and cost estimates. That is enabling more informed decision-making regarding circular alternatives. But the initiation should arise at organizational level which is promoting these adoptions to get long term benefits to client and competitive advantage to the contractors.

Secondly, the development of standardised pricing frameworks and cost databases for circular materials is essential. Industry bodies and regulatory authorities should collaborate with suppliers to establish reliable cost benchmarks. It can be used to reducing pricing uncertainty and improving market confidence. Such databases would support accurate cost estimation and facilitate fair comparison between linear and circular construction options. This initiation also should start with government level promoting sustainability.

Thirdly, procurement systems should transition from lowest-price tendering towards value-based selection methods that recognize life-cycle performance and sustainability outcomes. Contractual provisions that allow cost recovery for circular investments would further encourage adoption. Finally, policy support in the form of financial incentives, tax relief, subsidies for circular construction practices would enhance economic viability and accelerate market development. The governments can intervene to make these changes possible and to build the foundation of sustainable construction.

7. Conclusion

This study examined cost estimating barriers to circular economy adoption in the Sri Lankan construction industry using a mixed-method approach. The findings demonstrate that high initial costs, pricing uncertainty, inadequate life-cycle cost consideration, rigid procurement practices etc. significantly hinder CE implementation. Study integrated quantitative ranking with qualitative thematic insights. Results of the study provides a comprehensive understanding of how economic factors shape industry behaviour. The study contributes context-specific evidence to CE literature and offers practical recommendations for improving cost management, pricing strategies, as well as procurement frameworks to support circular construction in developing economies.

References

- Charef, R., Morel, J.C. and Rakhshan, K. (2021) 'Barriers to implementing the circular economy in the construction industry: A critical review', *Sustainability*, 13(23), 12989.
- Chileshe, N., Rameezdeen, R., Hosseini, M.R. and Lehmann, S. (2015) 'Barriers to implementing reverse logistics in South Australian construction organisations', *Supply Chain Management*, 20(2), pp. 179–204.
- Ellen MacArthur Foundation (2015) *Towards a Circular Economy: Business Rationale for an Accelerated Transition*.
- Ghisellini, P., Cialani, C. and Ulgiati, S. (2016) 'A review on circular economy', *Journal of Cleaner Production*, 114, pp. 11–32.
- Ghisellini, P., Ripa, M. and Ulgiati, S. (2018) 'Exploring environmental and economic costs and benefits of a circular economy approach to construction and demolition materials', *Journal of Cleaner Production*, 178, pp. 618–643.
- Häkkinen, T. and Belloni, K. (2011) 'Barriers and drivers for sustainable building', *Building Research & Information*, 39(3), pp. 239–255.
- Hosseini, M.R., Chileshe, N., Rameezdeen, R. and Lehmann, S. (2015) 'Reverse logistics in the construction industry', *Waste Management & Research*, 33(6), pp. 499–514.
- Jaillon, L. and Poon, C.S. (2014) 'Life cycle design and prefabrication in buildings', *Automation in Construction*, 39, pp. 79–88.
- Pomponi, F. and Moncaster, A. (2017) 'Circular economy for the built environment', *Journal of Cleaner Production*, 143, pp. 710–718.
- Rakhshan, K., Morel, J.C. and Charef, R. (2020) 'Barriers to reuse of construction materials', *Resources, Conservation and Recycling*, 152, 104508.
- Wijewansa, A.S., Tennakoon, G.A. and Waidyasekara, K.G.A.S. (2021) 'Implementation of circular economy principles during pre-construction stage: The case of Sri Lanka', *Built Environment Project and Asset Management*, 11(4), pp. 530–546.



ICRES

International Conference on
Resource Efficiency Towards Sustainability

**International Conference on
Resource Efficiency Towards Sustainability**

**CASE STUDIES AND BEST PRACTICES IN
CIRCULAR ECONOMY AND SUSTAINABILITY**

ICRES26_020

**CIRCULARITY IN CEMENT: INVESTIGATING THE USE OF BLAST FURNACE
SLAG: A CASE STUDY****V. Mahawaduge*, A. Pallegedara***Department of Manufacturing and Industrial Engineering, Faculty of Engineering, University of Peradeniya,
Sri Lanka.***Correspondence E-mail: virul-nimjaya.mahawaduge.2195@student.uu.se, TP: +94760927317*

Abstract: This case study attempts to investigate the way blast furnace slag is utilised in cement manufacturing, specifically focusing on the raw material mill in which it is added. Blast furnace slag, a wasteful by product in steel manufacturing, is re-routed to cement production, as a circular initiative. Descriptive statistics were used to diagnose variability in slag feed rates, and relevant literature was referenced to consider the impact of unmanaged slag variability. One year of data samples ($n = 5551$) taken on multiple occasions daily, are accessed, and the constituting components are studied. The cement plant used in this case study includes slag in its raw mixture and the resulting co-efficient of variation of slag was found comparably equivalent to most other raw meal components, measuring at 23%. Time series plots identified frequent fluctuations followed by box plots portraying pronounced outlier frequency in slag. Control loop architecture in raw material milling is analysed, identifying one example from existing literature, thereby finding that slag variability is not accounted for in adaptive control in this cement plant, as the other control indices, such as Lime Saturation Factor (LSF), etc. The case study aims to draw attention to the effects of slag variability as it propagates along the clinker manufacturing process, motivating the design of a control loop for slag feed rates. A conceptual schematic for how a new control loop could be integrated into existing control systems is conceptualised. Unlike prior work focusing on chemical moduli control, this case study highlights unmanaged slag feed variability as a blind spot in raw-meal control architectures. This study therefore frames slag variability as an overlooked control variable in raw meal optimisation.

Keywords: Clinker manufacturing; blast furnace slag; circular construction; control systems; statistical process control.

1. Introduction

Construction is one of many key hallmarks of a civilisation, where urbanisation and infrastructure are ubiquitous in any nation in the world. It is the key ingredient of concrete and the most consumed construction material worldwide according to Lehne and Preston, 2018. The authors of this study found that annual cement production surpasses four billion tonnes a year, whilst bearing responsibility for 8% of global carbon emissions. The study predicts that cement production demand will reach five billion tonnes annually by the year 2050. As production rises, it is important to mitigate and balance emissions, in accordance with the global Sustainable Development Goals (SDGs), SDG 15 Responsible Production, in particular.

Within the main process of cement production is clinker manufacturing. Clinker nodules are formed by sintering raw materials, and later ground with varying compounds to form various types of cement (Taylor, 2012). Blast furnace slag, a by-product of steel manufacturing, is now used as a clinker substitute (Lehne & Preston, 2018). Lehne and Preston, 2018, found that slag has been found to improve concrete durability and enhance workability, and by creating a bridge of circularity from steel production to cement production, slag has overall become a widely adopted alternative to virgin raw materials. However, integrating a new raw material into a large-scale production system comes with challenges. Within this study, we investigate the extent to which control systems within cement manufacturers, using a cement plant as a case study, account for feed rate variability in slag content.

This case study observes a cement plant which adopts slag and their approach to utilizing slag, whilst contemplating the efficiency of its adaptation. Slag, like any other material, can be added in varying amounts in a real-world process, operating at full scale. Control systems are employed to tackle issues regarding variability, by utilizing control indices such as Lime Saturation Factor, or Alumina Modulus, to name a few (Taylor, 2012.) Robust operating systems with lower process variability are known to operate more efficiently and therefore, less wastefully (Tsamatsoulis, 2024).

This system is widely adopted in raw meal sampling and our study aims to evaluate its effectiveness especially when considering SCMs like slag. The study by Tsamatsoulis 2024 did not tackle the integration of SCMs within its scope. Our study aims to bridge this gap by diagnosing feed rate variability in slag. It is possible that considerable slag variability may propagate downstream and alter cement properties, thereby destabilising the production of cement with quality control standards. In the modern era where resources are scarce, the efficient use of resources becomes vital for sustainable global development. This study investigates whether blast furnace slag feed variability constitutes an unmonitored operational variable in raw meal control systems.

2. Theoretical Background

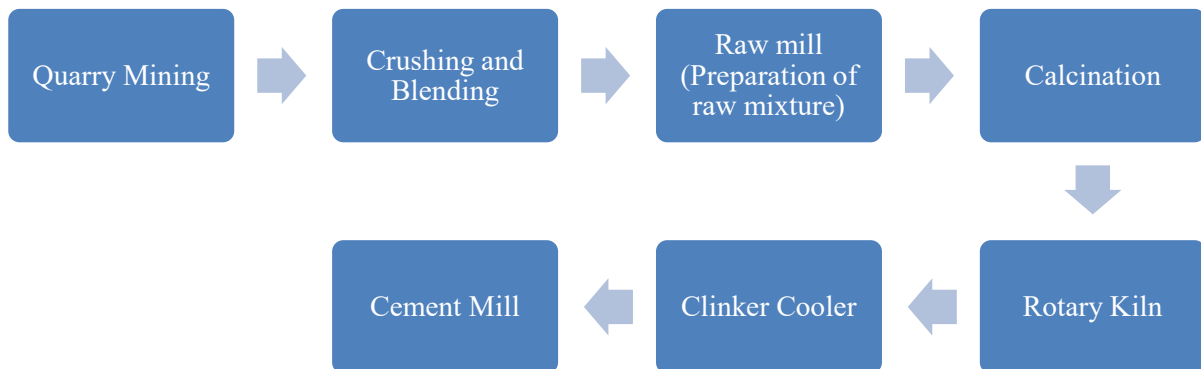


Figure 1 – Illustration of a typical cement manufacturing process (Hökfors, Eriksson and Viggh, 2014)

Figure 1 portrays the cement manufacturing process. Raw materials are gathered from quarries, such as limestone, and crushed and blended into a homogeneous stock. This stock is fed into a raw meal mill. The raw material mixture in clinker manufacturing typically consists of limestone, marl, sand, iron and varying other additives, such as supplementary cementitious materials, not limited to blast furnace slag or geopolymers (Taylor, 2012). Raw materials and supplementary cementitious materials are milled and consequently sintered. Sintering takes place after calcination in the cyclone tower, followed by heating in a rotary kiln and rapid cooling in the clinker cooler. Finally, clinker nodules are ground with materials such as gypsum in cement mills before the cement is transported to silos for storage. Blast furnace slag is added in the raw mill stage (Taylor, 2012).

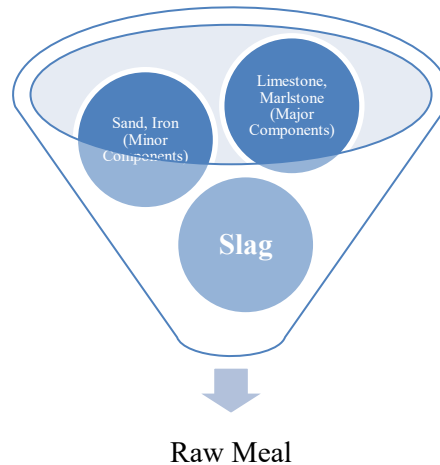


Figure 2: Composition of raw mix and raw mill – Taylor, 2012.

Figure 3 illustrates the control loop design adopted in the paper by Tsamatsoulis, 2024. By measuring Lime Saturation Factor, Silica Modulus, Alumina Modulus and other control indices, all of which are ratios balancing chemical compounds and alkali found in cement chemistry, Tsamatsoulis designed a robust adaptive control method for raw meal components.

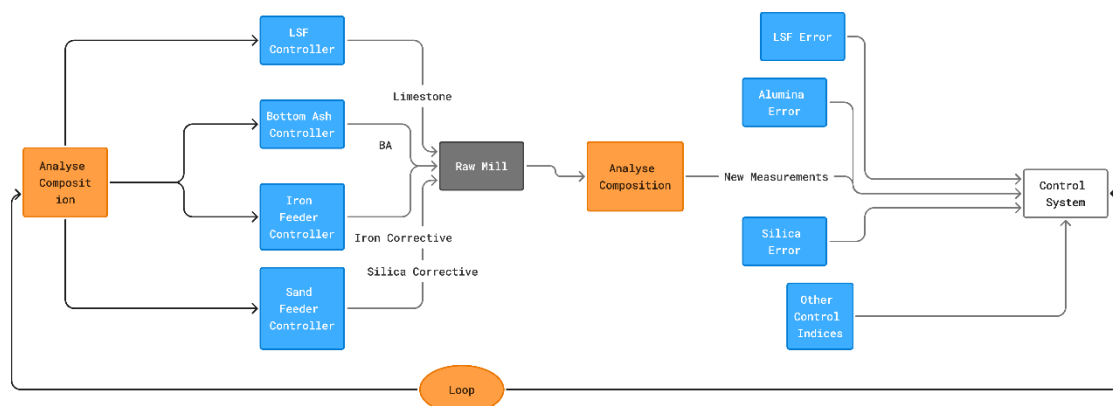


Figure 3: Conceptual block diagram of PID control loop – Tsamatsoulis, 2024.

By comparing targeted values against measured values, error is calculated in order to correctively adjust the feed rates of bottom ash (BA), iron, sand and lime (Tsamatsoulis, 2024). Figure 3 depicts an instance of control loop technology in feed rate optimisation in raw mills within cement manufacturing contexts. It is not taken from the cement plant studied for the case study but instead derived from standard control system practice as reflected by Tsamatsoulis, 2024. However, the study did not account for slag feed

rate, although it is possible the cement plant used in the paper’s case study does not integrate slag into its raw mix. On the other hand, the cement plant investigated within our investigation, and many more plants in Asia (Lehne & Preston, 2018) are adopting slag as a raw material. If control systems are not accounting for slag variability, downstream variability in cement quality may emerge consequently. While prior studies focus on chemical moduli control such as LSF and silica modulus, limited attention has been paid to the operational variability of supplementary cementitious materials such as blast furnace slag. This study therefore positions slag feed behaviour as an independent process variable requiring monitoring and potential control integration.

3. Methodology

The case study will analyse a database comprising compositional analyses of the raw mixer found in an anonymous cement plant in Northern Europe. The dataset comprises one year of samples taken automatically at hourly intervals. Initially, the range of values will be studied to consider if data cleaning would be required. To clean data, the summation of all compositional values will be calculated, and values that fall outside of 98-102% will be excluded as anomalous readings. Finally, the co-efficient of variation will be studied for each compositional constituent of the raw mixture.

This methodology is simple and therefore easily replicable using spreadsheet software, whilst delivering swift insights into slag variability through a dimensionless, relative quantification. The purpose of this investigation is to identify opportunities for improvement in process efficiency, and to discern if further investigation into slag feed rates should be required.

Temporal behaviour of raw meal constituents can be assessed using time-series visualisation. Box plots can in addition be used to examine distributional properties and dispersion. Such diagnostics can provide insights into variability structure and identify potential variables for further analysis.

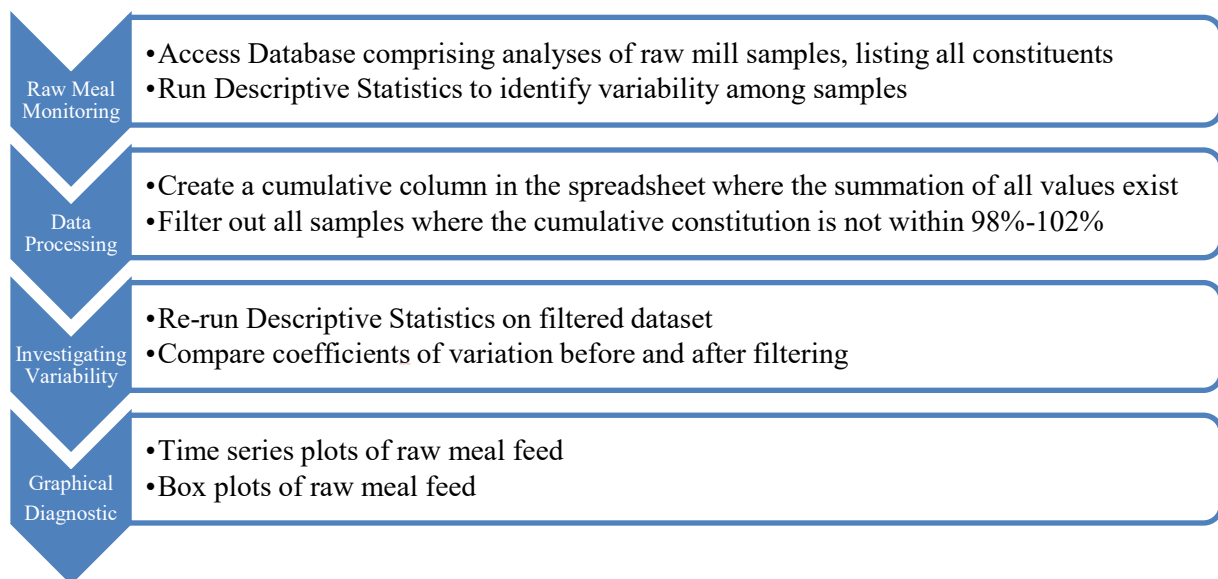


Figure 4: Process Flow Diagram for Case Study Methodology

This case study embarks to answer the below research questions:

- a. Can slag feed rate variability be observed relative to other raw materials?
- b. Do intervening solutions exist for observed variability?

4. Results and Discussion

Following the compositional analysis of the raw meal, the main components in this plant's raw mix are found to be limestone, marlstone, iron, sand and slag. In Table 1, the values for the raw mixer were taken without cleaning, and therefore, anomalous values and extremely large variability can be observed in the ranges of these values. In addition, a count of $n = 5551$ samples is utilised, as this dataset comprises an entire year's worth of samples. The following table contains the values post data cleaning.

After data processing, the filtered samples are investigated. The results in Table 1 show they comprise lower values overall for co-efficient of variation, and notably lower values for Range. In the filtered column, all values fall between 98 and 102% (± 2 uncertainty) for the total sum of values. This isolates measurements that are more likely to be accurate than the ones before filtering. Instances where the sum of all compositional constituents falls too short of 100% or exceed 100% are likely anomalous situations caused by random errors. Furthermore, of the 5551 samples, 5227 samples remained, thereby preserving 94.16%, essentially the majority, of the original unfiltered values.

Table 1: Statistical analysis of raw material data.

Raw Mix Components	Descriptive Statistics						Range Post Filter
	Variable	Total Count	Total Count Post Filter	CoefVar	CoefVar Post Filter	Range	
Limestone	Limestone	5551	5227	51%	35%	429.6	44.7
Marlstone	Marlstone	5551	5227	26%	9%	1250.2	47.4
Iron	Iron	5551	5227	79%	64%	7.6	1.1
Sand	Sand	5551	5227	48%	23%	58.8	4.1
Slag	Slag	5551	5227	32%	23%	28.8	3.3
Summation	Summation	5551	5227	26%	0.19%	1726.0	4.0

It becomes clear that slag variability is still clearly observable within raw mix composition, even after the data has been cleaned. While the exact threshold for a good co-efficient of variation is debatable, the results are not directly consistent with the control loop technology that has been visualised in the conceptual design, Figure 5. High variability can be observed, especially in iron feed rates, even post data cleaning. Therefore, it is natural for these compounds to be subjected to monitoring and robust adaptive control, employing systems as designed conceptually in Figure 3.

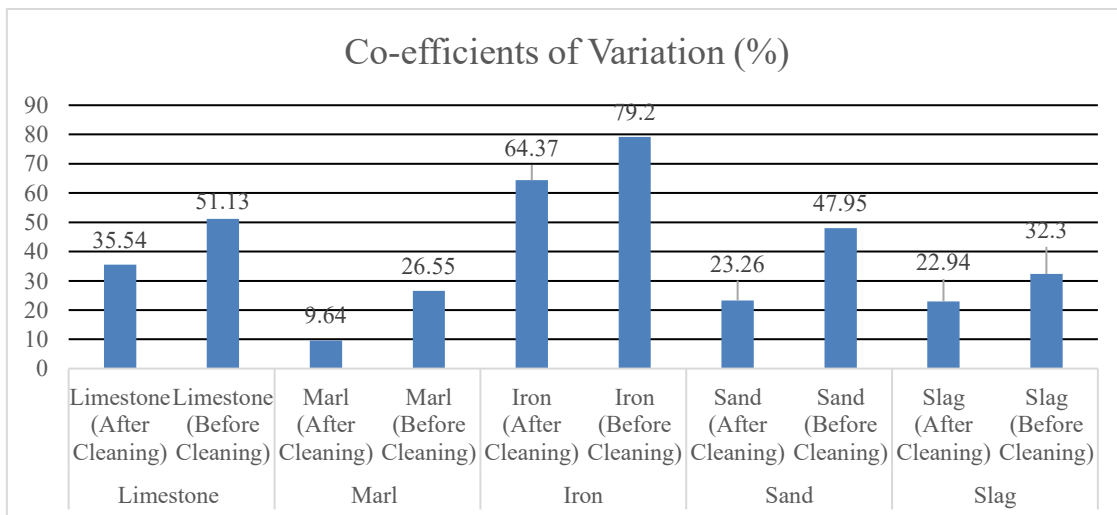


Figure 5: Bar Graph comparison of Coefficients of variation before and after data cleaning, in the raw mixture mill.

After cleaning, slag variability is comparable to sand but remains substantially higher than marlstone, despite being a chemically influential supplementary cementitious material. Since this plant exhibits slag variability, it is possible the plant has not yet implemented a control loop for slag content, as they have done for the limestone, sand, iron and other ratios. Introducing such a loop could yield statistically evident benefits. The CoV, can be minimised by utilising corrective and adaptive control technology. These samples are initially screened by temporal behaviour, visualised in the time series plots of the unfiltered and filtered datasets. These plots can be used to observe temporal fluctuations in feed rates. Furthermore, box plots of these values would enable visualisation of variability within each component individually.

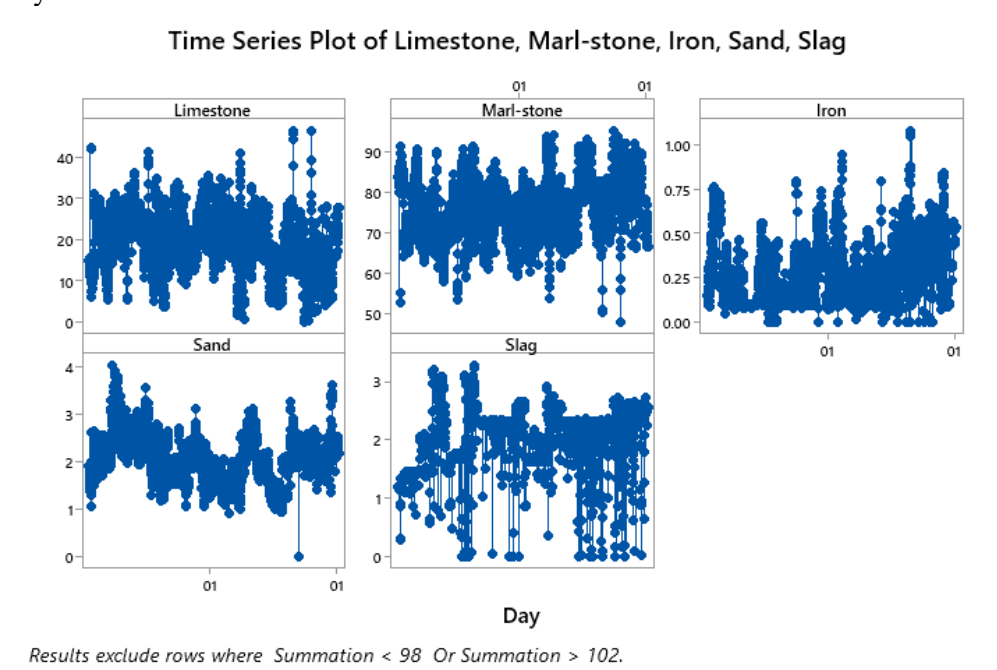


Figure 6: Time Series plot of filtered raw meal measurements

Considering a dataset spanning one year of samples, the plots in Figure 6 show frequent fluctuations in the main components of the raw meal. Closer inspection shows that slag feed rates have sharp and large vertical fluctuations the most among the components, suggesting that slag feed rates may be the most variable among raw material feed rates. To further confirm this claim, variability is visualised using the below box plots.

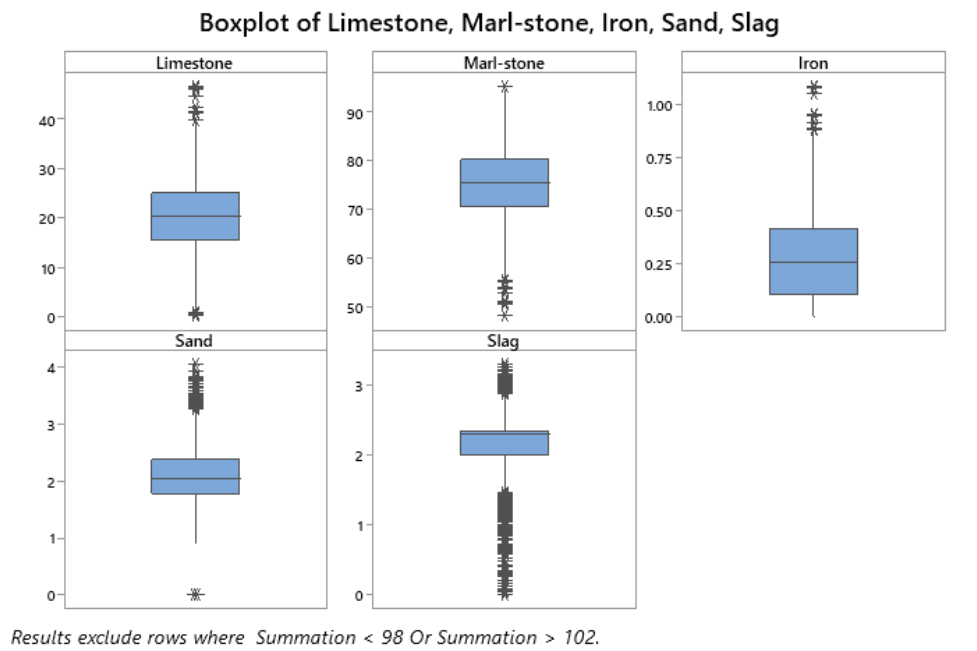


Figure 7: Box plots of filtered raw meal measurements

Figure 7 visualises the central tendency and dispersion within each raw meal constituent. Figures 7 and 8 identify that the largest components are limestone and marlstone, composing on average 20% and 75% of the raw meal respectively. Slag and sand are each centered around 2% of the total mix each, and iron content, while having the widest box, suggesting greater dispersion, barely contribute less than 1% of the raw mixture.

The most outliers can be observed for slag content, suggesting instability in slag feed rates relative to other components. While having the thinnest box, suggesting low dispersion, the sheer magnitude of frequency in outlier appearance warrants closer investigation of slag feed rate stability. These results indicate that slag variability behaves as an independent source of variation in the raw meal system. Unlike limestone or marlstone, slag exhibits high dispersion despite its relatively small contribution to the overall mix, suggesting it may represent an uncontrolled process input.

Despite the wide adoption of slag in cement manufacturing and its evidently unstable feed rate in this case study, exhibiting a 22.94% co-efficient of variation, it is questionable why slag feeders are not included in control loops, as shown in Figure 3. Future research could investigate whether slag variability bears enough concern for optimisation, and whether robust adaptive control of slag feed rates would yield a profitable return on investment. Quantifying the impact of reduced slag variability on KPI variability, such as alite content for example, would be one direction towards assessing the ROI of slag feed rate optimisation.

Minimising slag variation could in-turn reduce alite variability. One such study has found slag variability affects alite formation at the lab scale (Isteri et al, 2024). Alite is a key determinant of clinker quality, constituting 50-70% of OPC clinker (Staněk et al., 2002; Taylor, 2012). Laboratory studies suggest slag chemistry can influence alite formation (Isteri et al, 2024); however, plant-scale validation of this propagation was beyond the scope of this case study. Alite variability is one possible instance of unmanaged raw meal variability, specifically, slag variability, and there may be other KPIs compromised by unmanaged slag feed rate variation.

5. Conclusion

Blast furnace slag is added to cement manufacturing as a circular production initiative; however, it is unclear how many cement plants take steps to monitor and optimise slag feed rates. This case study demonstrated persistent longitudinal variability in slag feed behaviour within an industrial cement plant and established that this variability is structurally significant relative to other raw meal constituents. Time-series diagnostics, box plots, and descriptive statistics consistently indicated that slag variation forms a distinct component of the raw meal covariance structure, particularly following removal of measurement outliers.

Poorly managed feed rates with high variability could influence cement product quality as variance propagates from the raw materials to the finished products, effectively undermining the intended initiative. To produce quality clinker whilst adopting circular technological initiatives, resource management techniques, such as statistical process control, specifically automatic control systems, could be deployed to better manage slag feed rate variability.

Therefore, plant scale clinker manufacturing could realise quality improvement potential, by reducing slag variability. Future work could aim to explore potentially commercialisable control loop designs for implementation. One such example is conceptualised below, in Figure 8.

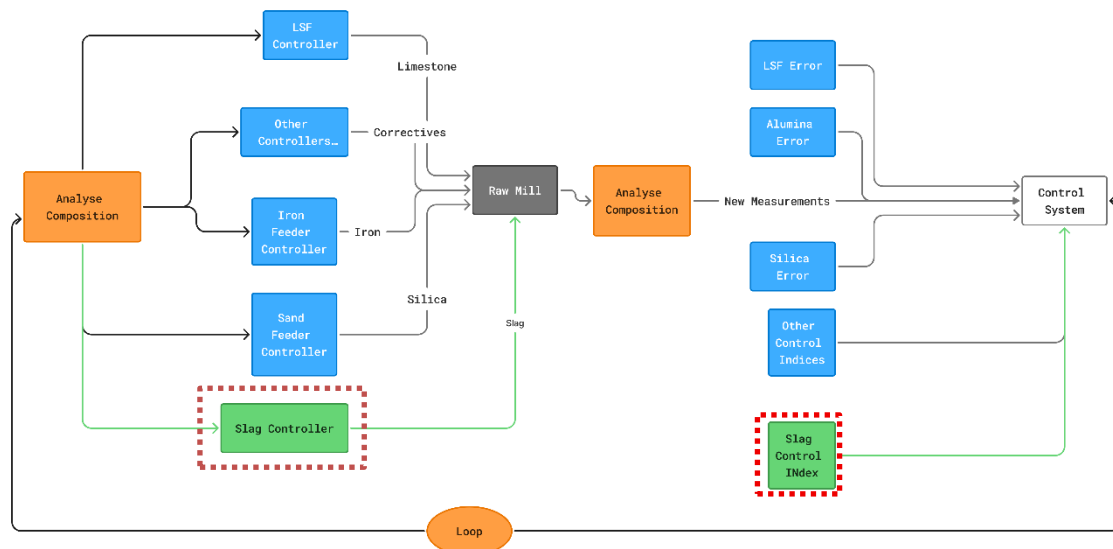


Figure 8: Proposed control loop design.

Control system architecture is heterogeneous among cement plants, depending on their process control strategies and manufacturing methods. Therefore, the Other Controllers block was included as a placeholder for other non-specific yet essential control indices. This control loop requires the development of a mathematically formulated control index for slag content, using which the slag feed rates could be controlled. Further research would be needed to derive this index. However, its development would culminate in the enabled monitoring of slag feed rates. As a result, slag variability could be reduced at the raw mill stage, using corrective adaptive control. It could be used to target lower energy consumption metrics whilst maintaining product quality (Andrade Neto *et al.*, 2025). This would be achieved by the control loop's immediate objective of adaptively and correctively adjusting slag feed rates for optimal clinker quality.

Acknowledgements

The authors thank the anonymised cement plant for access to the provided databases.

References

- Andrade Neto, J.S., Carvalho, I.C., Monteiro, P.J.M., de Matos, P.R. and Kirchheim, A.P. (2025). Unveiling the key factors for clinker reactivity and cement performance: A physic-chemical and performance investigation of 40 industrial clinkers. *Cement and Concrete Research*, 187, p.107717. doi:<https://doi.org/10.1016/j.cemconres.2024.107717>.
- Hökfors, B., Eriksson, M. and Viggh, E. (2014) Modelling the cement process and cement clinker quality. *Advances in Cement Research*, 26(6), pp. 311–318. <https://doi.org/10.1680/adcr.13.00050>
- Isteri, V., Ohenoja, K., Rößler, C., Kletti, H., Tanskanen, P., Illikainen, M., Hanein, T. and Fabritius, T. (2024) The effect of slag variability in the attempted manufacture of A₂F (alite-ye'elimate-ferrite) cement clinker at both laboratory and pilot scale. *Cement*, 16, 100098. <https://doi.org/10.1016/j.cement.2024.100098>
- Lehne, J. and Preston, F. (2018) *Making Concrete Change: Innovation in Low-Carbon Cement and Concrete*. London: Chatham House.
- Staněk, T. and Sulovský, P. (2002) The influence of the alite polymorphism on the strength of the Portland cement. *Cement and Concrete Research*, 32(7), pp. 1169–1175. [https://doi.org/10.1016/S0008-8846\(02\)00756-1](https://doi.org/10.1016/S0008-8846(02)00756-1)
- Taylor, N. (2012) *Introduction to Cement Process Technology*. Geelong, VIC: Intec Services Pty Ltd.
- Tsamatsoulis, D. (2024) Robust adaptive control system of variable sampling period for cement raw mix quality control. *ChemEngineering*, 8(6), 113. <https://doi.org/10.3390/chemengineering8060113>.

ICRES26_028

FISH MEAL VALUE CHAIN: AN INVESTIGATION ON CIRCULAR SOLUTIONS AND CHALLENGES IN SRI LANKA

D.A.M. De Silva¹, N.H. A Vikumsara^{1*}, I.M. Wickramarathna¹, Nikita Gopal², M.M.S.C. Senevirathne¹

¹*Department of Agribusiness Management, Faculty of Agricultural Sciences, Sabaragamuwa University of Sri Lanka, Belihuloya, 70140, Sri Lanka.*

²*ICAR-Central Institute of Fisheries Technology, Kochi, India*

**Correspondence E-mail:nh.amalki99@gmail.com, TP: +94772371520*

Abstract: Fish waste generation from wholesale, retailing and processing activities presents a significant environmental challenge and resource loss in Sri Lanka's fisheries sector. This study investigates circular economy solutions within the fish meal value chain by identifying practical circularity strategies for fish waste reuse, investigating market opportunities, and discovering solutions for small-scale producers and women fish processors. The research employed a mixed-methods approach, conducting case studies at two sites: Kudawella, which is a small-scale, women-led fish meal production and Peliyagoda Central Fish Market, which is an industrial-scale facility. Data collection included structured field observations, market mapping, two focus group discussions in Kudawella and in-depth interviews with key value chain actors. Data were analysed using value chain analysis, thematic analysis, and descriptive statistics. Findings reveal two distinct circular businesses. In Kudawella, 93% of fish processors produce Maldive fish, with processing waste, which are bones and leftovers, recycled into fish meal through simple drying and milling. The fish meal is rich in calcium and potassium, which is bought by poultry farms and aquaculture farms. At Peliyagoda, an industrial-scale system converts mixed daily market waste into four products: sterilised fish meal, organic fish bone meal, fish soluble paste, and crude fish oil. The study reveals that fish waste valorisation is technically and economically feasible at multiple scales. However, small-scale circular models remain constrained by limited drying space, weather variability, and informal market linkages, while women processors remain marginal to value capture. Scaling circular fish waste businesses across Sri Lanka requires targeted investment in processing infrastructure, formal contracts securing waste supplies and product markets, and supportive policies that recognize circular business models as a strategy to both food security and environmental management.

Keywords: circular economy; fish waste; fish meal; valorization; supply chain; women processors; Sri Lanka

1. Introduction

The world fisheries and aquaculture sectors represent two major aspects of food security, nutrition, and livelihood. Fish is the primary source of animal protein in developing countries. Around 70% of processed fish, about heads, fins, skin, bones, and guts, are discarded as waste (Food and Agriculture Organization(FAO), 2021). Globally marine fisheries alone generate annual waste of 9.1 million tons, which is a loss of valuable biomass and missed economic opportunity (FAO, 2021).

Sri Lanka presents a critical research location to understand the value chains of fish waste and to implement circular solutions. As an island with over 500,000 Km² of fishing rights and an aquaculture sector, fisheries and aquaculture industries contribute 1.3% of the country's gross domestic production and employ 2.7 million people on harvesting, processing, trading, and related livelihoods (Ministry of Fisheries, 2019). Fish is responsible for more than 50% of animal protein intake in the country, with per capita consumption about 15.1 to 17.3 kilograms annually (FAO, 2018). The country's total annual fish production of 485,770 tons divided across three subsectors, coastal fisheries (46%), deep-sea and offshore fisheries (35%), and inland fisheries and aquaculture (19%) (FAO, 2018). Other than extensive production, Sri Lanka faces challenges in utilising fish loss and waste management. Post-harvest losses in deep-sea and offshore multiday fisheries range from 40–60%, and fish waste is generated annually by tuna processing plants (Ahamed Rifath et al., 2023). At Peliyagoda fish market, four metric tons of fish waste are produced daily, of which only one ton is used for value-added production, such as fish meal manufacturing (Jayathilake, 2020). The causes of fish loss and waste in Sri Lanka can be categorised as follows: poor onboard handling and storage practices during multiday fishing, which degrade fish quality; and inadequate infrastructure at landing sites, including insufficient ice facilities and inappropriate storage conditions, which accelerate post-harvest deterioration (FAO, 2018). Transportation challenges, insufficient equipment at fish markets, and weaknesses in processing technology contribute to quality degradation and value loss. These challenges are deepened by broader challenges such as, the cost of cold chain infrastructure, access to credit for upgrading vessels and facilities, and consumer awareness of fish quality (FAO, 2018).

The circular economy offers a framework to transform fish waste into an opportunity for economic growth, and enhanced food security. The circular economy is designed to mimic natural regenerative systems, in which waste does not exist but is instead converted into feedstocks for subsequent production cycles (FAO, 2018). In fisheries sector, this means reimagining fish processing by products which are traditionally disposed of through landfilling, ocean dumping, or burning as valuable raw materials for diverse downstream industries. With the scientific and technological advances now fish waste can be transformed into an expanding portfolio of high-value products such as Collagen and Gelatine for cosmetics and pharmaceuticals, omega-3 oils and other lipid-based nutraceuticals, Chitin and Chitosan for food additives and biodegradable packaging materials, protein hydrolysates for functional food ingredients, organic fertilizers and animal feed supplements, and specialized compounds with antimicrobial and antioxidant properties (Venugopal, 2021; Espinales et al., 2023). Iceland's seafood sector shows that the commercial feasibility of such approaches through integrated valorisation, a single Atlantic cod fish valued at approximately \$12 for its fillets, can generate over \$5,000 in revenue through co-product development, with white fish utilisation rates reaching 80% (Seafish, 2025).

1.1 Circular solutions for fish waste

Fish processing generates waste of 40–60% of total fish weight. 70% of processed fish including heads, fins, skins, bones, and guts is discarded as waste despite containing protein 12–30%, lipids 0.4–46%, and minerals 1–50% with significant nutritional and commercial value (Gaikwad & Kim, 2024; Nikoo et al., 2023). Seafood processing waste disposed of through landfilling or burning contributes 9.66 kg CO₂-equivalent climate change burden per kilogram of raw material processed (Iñiguez-Moreno et al., 2024). Global research initiatives recognise fish waste as a strategic resource. The European Union's Common Fisheries Policy and Blue Growth Strategy encourage circular bioeconomy with the EU blue economy generating 5.4 million jobs and €500 billion in gross value annually (Cooney et al., 2021). The Asia-Pacific region demonstrates rising resolve, as quick

aquaculture increase is associated with 35–70% food loss and waste across supply chains (Türkten et al., 2023). Table 01 presents the key findings of the selected papers related to the applications of fish waste in the circular economy in the global scenario.

Table 1: Selected studies on circular approaches on fish waste management












Author(s)		Country of Origin	Key Research Focus
Gaikwad & Kim	2024	Republic of Korea 	Fish collagen extraction methods (ASC, ESC, UAE, DES, SFE) and biomedical applications
Nikoo, Regenstein, & Yasemi	2023	Iran / USA 	Fish protein hydrolysates production, bioactivity, antioxidant and ACE inhibition
Jimenez-Champi, Romero-Orejon, Muñoz, & Ramos-Escudero	2024	Peru 	Fish byproduct revalorization bioactive compounds and food applications
Türkten, Bostan, & Karaman	2023	Turkey 	Food loss and waste quantification across production scales and environmental efficiency
Moreno, Romero, Melchor-Martínez, Parra-Saldívar, & González-González	2024	Mexico 	Chitosan extraction and valorization: chemical, biological, and emerging technologies
Cooney, O’Neill, Whelan, & Fitzpatrick	2021	Ireland 	Circular economy framework for seafood waste valorization and EU policy context
Venugopal	2021–2022	India 	Comprehensive reviews on fish waste valorization, green processing, and circular bioeconomy
Khiari, Tebsi, Ben Ali, Romdhane, & Laroche	2022	Tunisia / France 	Cold-adapted proteolytic enzymes from cold-water fish for sustainable waste valorization
Hassoun, Pasini, & Hough	2023	Italy / Argentina 	Industry 4.0 technologies for reducing and valorizing seafood waste
Abejón	2022	Spain 	Membrane processes for recovery and separation of bioactive compounds from seafood waste
Xia, Mu, Li, & Zhang	2024	China 	Extraction and valorization strategies of seafood byproducts with focus on waste-to-value



Figure 1: Results of the content analysis of the keywords of the published research – word cloud

Figure 1 presents the frequency and significance of concepts in studies on the fish-waste value chain, circular-economy strategies, and implementation challenges. Leading terms such as “fish waste,” “valorisation,” “circular economy,” “sustainability,” and “blue economy” mirror the major focus on converting fishery by-products into value-added products. Supporting terms including “organic fertiliser,” “fermentation,” “post-harvest losses,” “infrastructure,” “policy gaps,” and “environmental impact” highlight frequent solutions and barriers.

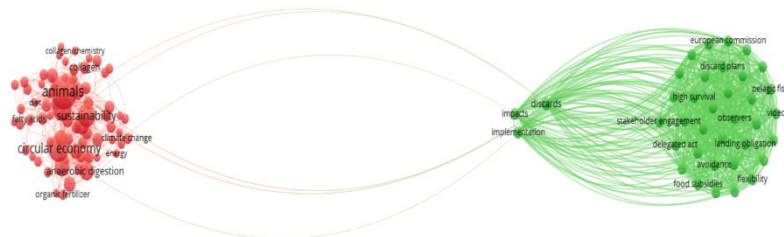


Figure 2: Keyword connection developed from the published literature on fish waste and circularity

This bibliographic map was generated through a query-based text search combining "circular" AND "fish waste," retrieving literature on circular economy principles and fish-processing waste valorisation. The red cluster represents the bio-technological valorisation, centred on biochemical extraction and materials science applications, including collagen, fatty acids, animal products, sustainability, the circular economy, anaerobic digestion, and organic fertiliser. The green cluster represents policy and governance implementation related to fisheries management and regulatory frameworks, including the *European Commission*, *discard plans*, *high survival*, *stakeholder engagement*, *delegated acts*, *landing obligation*, *food subsidies*, and *video observers*. This cluster reflects the institutional mechanisms and regulatory instruments that create economic incentives and legal obligations for the valorisation of waste.

2. Materials and methods

2.1. Location

The study employed a mixed-methods approach that integrated quantitative and qualitative methods to address the research objectives. This study was conducted in Kudawella and at the Peliyagoda central fish market in Sri Lanka (Figure 3), focusing on two case-study respondents: a small-scale fish meal producer in Kudawella and a large-scale fish meal producer in Peliyagoda.

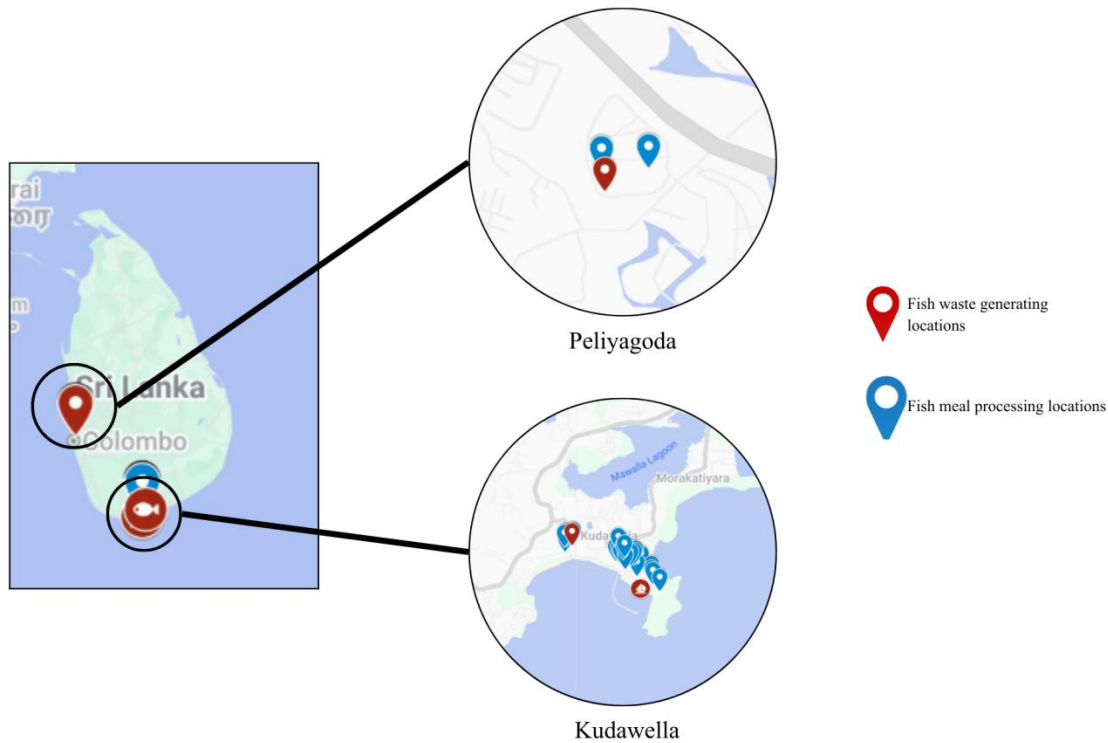


Figure 3: Study locations of Kudawella and Peliyagoda fish processing clusters

2.2. Data Collection and Analysis

To achieve the research objectives, a combination of qualitative and quantitative methods was employed. To identify circularity strategies for the reuse of fish waste, interviewer-administered structured questionnaire and observations were conducted at two case studies; the information was analyzed using value chain analysis, and descriptive statistics to examine the market landscape of the fish meal value chain. Field observations and in-depth interviews were conducted with owners, suppliers of semi-processed dried fish bones (Maldivian fish processors from the Kudawella fish processing cluster), and fish waste suppliers at the Peliyagoda wholesale fish market. Finally, to explore value chain integration strategies for SMEs and women fish processors, in-depth interviews and focus group discussions were conducted, and qualitative thematic analysis was applied to identify challenges and strategies.

Table 2: Operationalization table for the study

objective	variables	data collection tools	analytical tools	expected outcomes
1. To identify circularity strategies employed for reuse of fish waste	fish waste reuse practices value addition pathways value chain actors and linkages operational processes knowledge and capabilities	Filed observations, market mapping, in-depth interviews with key informants	Value chain analysis, Gioia content analysis, thematic analysis	Identification and categorization of circularity strategies

	institutional and regulatory context market demand and viability			
2. To find out the market landscape of the fish meal value chain of Sri Lanka	Micro environment: raw material suppliers, machinery suppliers, collectors, local government authority, end users, transport and logistics Macro-level variables: competitors, importers, national regulatory and legal framework, market trends, economic factors	Field observations, market mapping, in-depth interviews with key informants	Market landscape of the fish meal value chain of Sri Lanka	Market map or market landscape of fish meal
3. To explore value chain integration strategies for SMEs and women fish processors into fish meal value chain and challenges	Access to raw materials processing equipment availability storage and drying facilities access to credit/loans working capital availability linkages with fish meal producers transport facilities storage and processing space participation in the fish waste supply profitability	in-depth interviews and focus group discussions	Descriptive statistics thematic analysis	To adapt and contextualize global circular economy frameworks into a locally appropriate framework, circular business model for the fish waste

3. Results and discussion

The present study has identified a waste valorisation-based circularity strategy adopted in two case studies in Kudawella and Peliyagoda, in which fish processing residues are converted into value-added fishmeal. Fish waste generated from Maldivian fish and dry fish processing activities is collected and reused instead of being disposed of as waste (Figure 4). These residues are processed into fish meal, which is sold at LKR 200.00 per kg to poultry farms, fish feed producers, and prawn farming establishments. Poultry farms account for the largest share, representing 60% of total fish meal sales (Figure 5). The majority of poultry farms, as the main buyers of fish meal, indicate the high demand for Calcium-rich feed in the poultry industry (Ramachandra et al, 2025). Maldivian fish residues are purchased at LKR 100.00 per kg, while dry fish residues are purchased at LKR 50.00 per kg due to their higher salt content and the absence of boiling during processing. Boiled fish residues are easier to mill when processing fish meal.

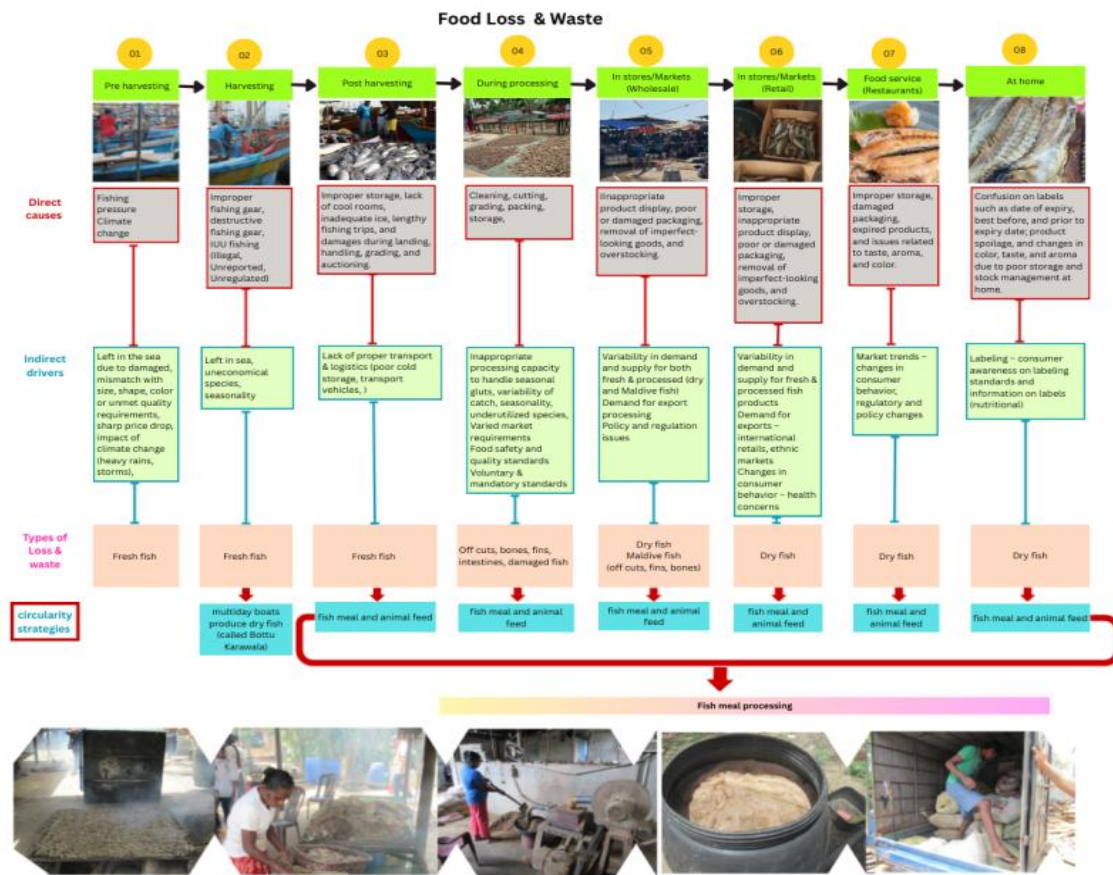


Figure 4: Fish loss and waste value chain along with the circular entry points and key steps of fish meal processing and distribution of the Kudawella case study

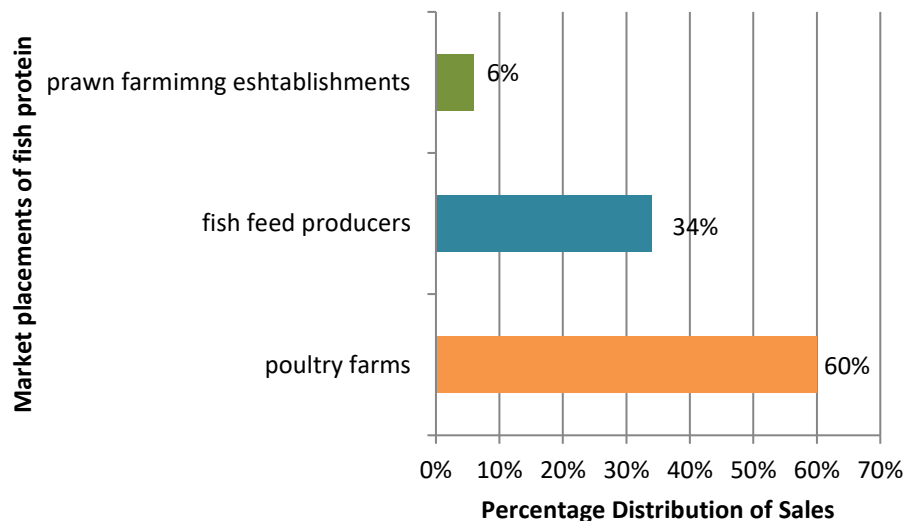


Figure 5: Percentage distribution of fish meal sales across market destinations

The producers distribute the finished fish meal using their own transport facilities to areas including Chilaw, Kurunegala, Negambo, Peliyagoda and Ranna (figure 6). All transactions are conducted on a cash basis to ensure continual business operations. Although there is a very high market demand for its protein, the producer lacks sufficient production capacity to meet this demand, mainly due to

processing constraints. At Peliyagoda fish market, animal fish meal is distributed to animal feed producers and also directly exported (figure 6).

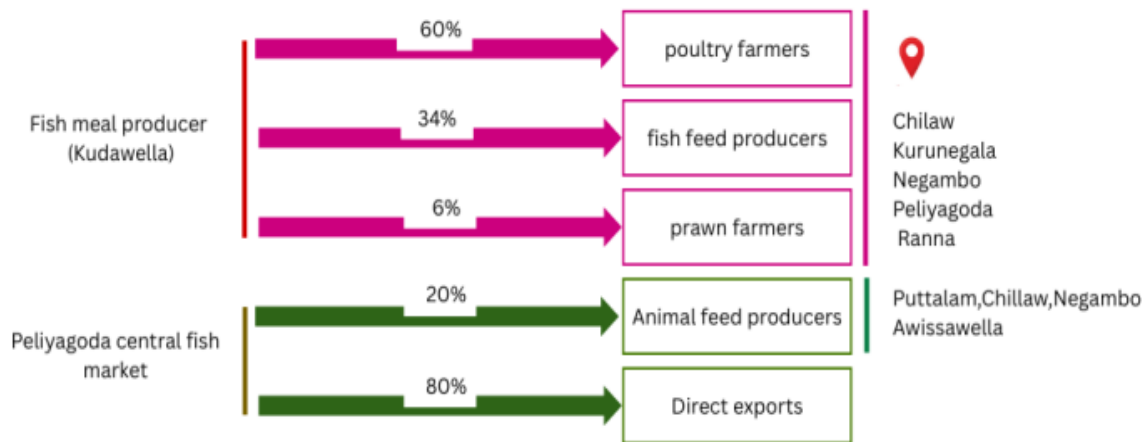


Figure 6: Distribution channel of the fish meal from producer (Kudawella) to regional buyers

Peliyagoda Central Fish Market, the largest wholesale and retail fish market in Sri Lanka, handles a wide variety of finfish and shellfish, generating significant daily waste. A fish meal production facility within the market converts this waste into high-value products, including steam-dried, sterilised fish meal, fish oil, fish soluble paste, and organic fertiliser, applying circular economy principles (figure 7). This not only addresses environmental hazards but also creates economic value and enhances nutrient availability for animal feed (Kolawole & Mustapha, 2023).

Other than fish meal following products are produced in the Peliyagoda fish meal production plant. The fish soluble paste, a fishmeal and fish oil by-product, is rich in dissolved proteins and a high level of amino acids (Jayaweera et al., 2024). It is used as a feed attractant to increase the palatability of feed to enhance the appetite and feed intake of aquatic animals, promoting growth and development, and improving breeding efficiency (Rahman, 2023). It is also used as fertiliser as well as in the agriculture industry and it adds nutrients to the soil (Dasanayake, 2022)

Crude fish oil is the oil that's extracted from fish and fish byproducts enriched with protein, fat and Omega 3 essential fatty acids eicosatetraenoic acid (EPA) and docosahexaenoic acid (DHA) has a high nutrient value (Badoni et al., 2021). The crude fish oil manufactured in the plant provides high-quality crude fish oil crafted from the most fresh and chemical-free fish and fish by-products (Jayasekara et al., 2022).



Figure 7: Fish loss and waste value chain along with the circular entry points and key steps of fish meal processing at Peliyagoda fish market

In Kudawella, most of the women fish processors mainly produce Maldivian fish (93%) (figure 8) due to Women fish processors have explored alternative livelihood strategies by engaging in Maldivian fish processing. They utilise underutilised marine fish species, including *Linna* (*Deapterus russelli*), *Balaya* (*Katsuwonus pelamis*), *Kelawalla* (*Thunnus albacares*), and *Pothubari* (*Lutjanus* spp.), particularly second-grade fish. Their contribution is crucial for ensuring food fish security, providing protein supplementation to local communities and the diaspora, managing fish loss and waste,

conserving resources, and promoting circular economy principles, while only a very few dry fish processors (7%) are involved in dry fish production.

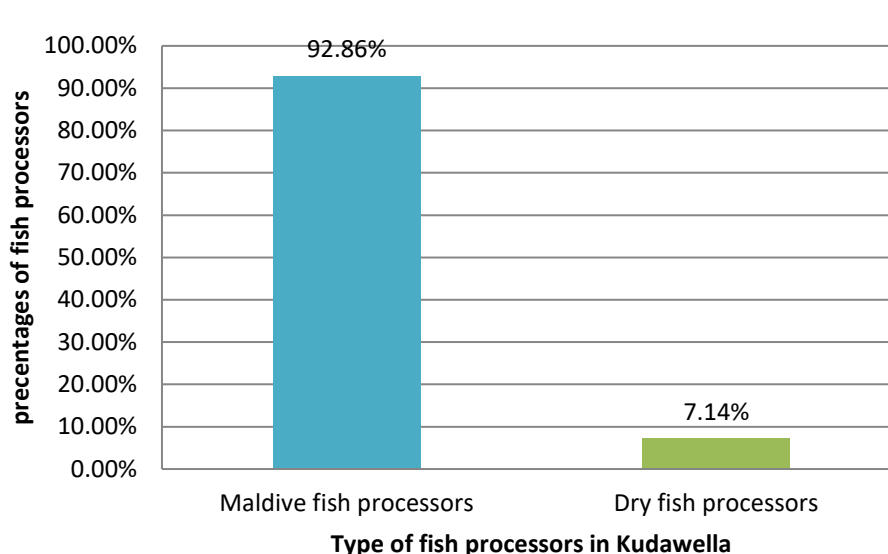


Figure 8: Percentage of producers involved in Maldivian fish and dry fish production in Kudawella

In Kudawella, Pothubari (*lutjanus spp*) contributes the highest share of fish waste, accounting for 30% of the total (Table 3).

Table 3: species-wise typology of fish waste from different fish species in Kudawella and Peliyagoda fish market

location	fish species	type of waste	percentage of total waste (%)
Kudawella	Linna (<i>Deapterus russeli</i>)	heads, bones	25%
	Balaya (<i>Katsuonus pelamis</i>)	heads, bones	22%
	Kelawalla (<i>Thunnus albacares</i>)	heads, bones	22%
	Pothubari (<i>Lutjanus spp</i>)	heads, bones	30%
Peliyagoda fish market	Balaya (<i>Katsuonus pelamis</i>)	heads, bones, gut	25%
	Kelawalla (<i>Thunnus albacares</i>)	heads, bones, gut	25%
	Thalapath (<i>Istiophorus platypterus</i>)	heads, bones, gut	25%
	Thora (<i>Scomberomorus commerson</i>)	heads, bones, gut	25%
	Other Small fin fish species	Head, gut	22%

Giogia analysis indicates that circularity strategies for fish waste reuse are primarily influenced by waste characteristics, business scale, infrastructure availability, and environmental conditions. Effective implementation is enabled by knowledge of waste reuse technologies, institutional support, and strong market demand for fish-based by-products (figure 9).

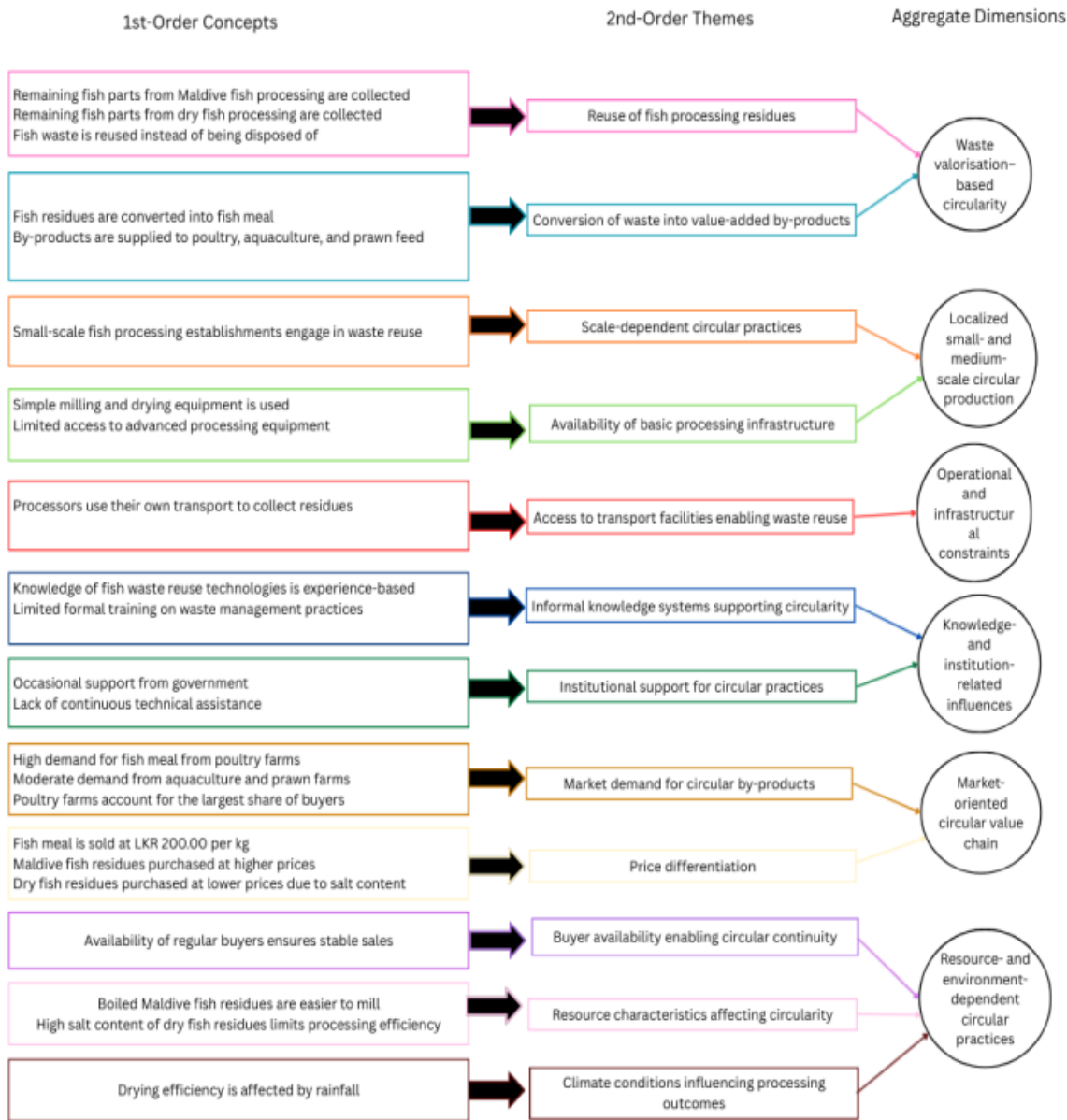


Figure 9: Giogia analysis based on in-depth interviews with key informants in Kudawella

Table 4: Comparison of circularity strategies for fish waste reuse in Kudawella and Peliyagoda

Aspect	Kudawella	Peliyagoda Central Fish Market
Type of circular economy model	Localised, small-scale circular economy model	Large-scale, industrial circular economy model
Primary source of fish waste	Residues from Maldive fish and dry fish processing units	mixed daily fish waste from wholesale and retail market operations
Key fish species utilized	Linna (<i>decapterus russelli</i>), Balaya (<i>katsuwonus pelamis</i>), Kelawalla (<i>thunnus albacares</i>), Pothubari (<i>lutjanus spp.</i>)	diverse fin fish and shellfish species handled at the central market
Main circular products	Fish protein used for animal and aquaculture feed	steam-dried sterilized fish meal, organic fish bone meal, fish oil, fish soluble paste, organic fertilizer

Circularity strategy employed	Direct reuse of locally generated fish residues as raw material for fish protein production	valorisation and industrial bioprocessing of large volumes of fish waste into multiple high-value by-products
Processing characteristics	Simple processing; quality highly dependent on proper drying and salt content of residues	advanced processing including cooking, steaming, sterilization, oil extraction, and by-product recovery
Market linkages	strong backward linkages with local fish processors; localized distribution	strong forward linkages with animal feed, agriculture, and aquaculture industries nationwide
Sale of operation	small-scale with limited production capacity	large-scale, centralized production facility
Key constraints	inadequate drying technology, and limited infrastructure	fewer raw material constraints due to large waste volume; capital and technologyintensive
Environmental contribution	reduces local waste disposal and preserves value within the community	mitigates large-scale waste disposal risks and environmental pollution at the national level
Global recognition	Not a globally recognized method	Only Food and Agriculture Organization(FAO) approved fish waste reuse facility in Sri Lanka

Table 5: value chain integration strategies of SMEs and women fish processors into the fish meal value chain: a comparison between Kudawella and Peliyagoda

Aspect	Kudawella	Peliyagoda Central Fish Market
Key actors involved	women Maldive fish processors, dry fish processors, small-scale fish protein producer	fishermen, wholesalers, waste collectors, fish meal processing company
Role of women processors	primary generators of fish residues through Maldive fish and dry fish processing	limited direct involvement, women mainly engaged in fish handling and retail activities
Type of value chain integration	informal, backward-linked integration with local fish processors	formal, centralized integration through organized waste collection and processing
Integration strategy	direct sale of fish residues from women processors to fish protein producer	collection of mixed market waste supplied to centralized fish meal production plant
Nature of linkages	strong backward linkages with local processing units	strong forward and backward linkages across national feed and fertilizer markets
Value addition mechanism	conversion of residues into fish protein for poultry and aquaculture feed	multi-product valorisation (fish meal, fish oil, fish soluble paste, fertilizer)
Market access	local and regional markets (Chilaw, Kurunegala, Negombo, Ranna,)	national-level markets supplying animal feed and agriculture sectors
Pricing & income opportunities	residue prices influenced by processing methods (boiling, salt content, drying quality)	stable pricing due to standardized processing and large-scale production
Challenges	limited drying space, climate impacts, lack of technology, inconsistent residue supply	high capital requirements, operational complexity
Infrastructure availability	minimal infrastructure, reliance on traditional drying methods	advanced infrastructure, including steam drying, sterilisation, and oil

		extraction
Scalability of integration	low scalability due to raw material and infrastructure constraints	high scalability supported by large waste volumes and processing capacity
Contribution to livelihoods	enhances income opportunities for women processors through waste monetization	generates employment but with limited empowerment of women processors

4. Conclusion

This study shows that fish waste in some areas of Sri Lanka is already entering formal circular business models, but these remain underutilised and unevenly supported. In Kudawella, women-led Maldivian fish and dried fish processing units convert fish heads and bones into protein-rich fish meal, which is sold primarily to poultry and aquaculture farms. In Peliyagoda, a large-scale industrial facility transforms mixed daily market waste into steam-dried, sterilised fish meal, organic fish bone meal, fish oil, fish soluble paste and organic fertiliser. Together, these two cases demonstrate that fish waste can be systematically redirected away from land and water dumping.

The findings highlight two main circular strategies for the reuse of fish waste. Kudawella represents a localised, low-technology circular model in which women processors and a small-scale fish meal producer directly reuse processing residues through simple drying and milling. This circular business depends on waste characteristics, weather conditions and basic infrastructure such as drying space and storage. In difference, Peliyagoda operates a high-capacity, technology-intensive model based on the continuous collection of diverse market waste and its conversion through boiling, steaming, sterilisation, and oil extraction.

The fish meal value chain is shaped by strong demand from poultry, aquaculture and agriculture sectors. In Kudawella, fish meal produced from Maldivian fish and dried fish residues is sold directly to poultry farms, which is 60% of total sales. In Peliyagoda, advanced processing and centralised waste collection allow a broader range of products, for fertiliser users and international buyers.

The study reveals both opportunities and barriers for integrating SMEs and women fish processors into the fish meal value chain. In Kudawella, women processors are the key circular actors, generating residues and benefiting directly from residue sales, thereby turning waste into an additional income stream. Their integration remains informal and vulnerable. At Peliyagoda, value chain integration is more formal and capital-intensive.

Overall, the two case studies confirm that circular fish waste valorisation can simultaneously reduce environmental problems, increase resource-use efficiency, and enhance rural and urban livelihoods. A supportive environment, including infrastructure investment, technical training, quality and safety standards, and incentives for circular business models, is required to scale up these initiatives.

References

- Abejón, R. (2022). Seafood processing by-products by membrane processes. *Current Research in Environmental Sustainability*, 4, 100141. <https://doi.org/10.1016/j.crsust.2022.100141>
- Cooney, R., O'Neill, E., Whelan, K., & Fitzpatrick, B. (2021). A circular economy framework for seafood waste valorisation: Aligning ocean economy goals with circular economy principles. *Marine Policy*, 127, 104435. <https://doi.org/10.1016/j.marpol.2021.104435>
- Gaikwad, S., & Kim, M.J. (2024). Fish by-product collagen extraction using different methods and their application. *Marine Drugs*, 22(2), 60. <https://doi.org/10.3390/md22020060>
- Hassoun, A., Pasini, F., & Hough, G. (2023). Use of industry 4.0 technologies to reduce and valorize seafood waste. *Comprehensive Reviews in Food Science and Food Safety*, 22(3), 2215–2245. <https://doi.org/10.1111/1541-4337.13149>
- Iñiguez-Moreno, M., Santiesteban-Romero, B., Melchor-Martínez, E.M., Parra-Saldívar, R., & González-González, R.B. (2024). Valorization of fishery industry waste: Chitosan extraction and its application in the industry. *MethodsX*, 13, 102892. <https://doi.org/10.1016/j.mex.2024.102892>
- Jimenez-Champi, D., Romero-Oregon, F.L., Muñoz, A.M., & Ramos-Escudero, F. (2024). The revalorization of fishery by-products: Types, bioactive compounds, and food applications. *International Journal of Food Science*, 2024, 6624083. <https://doi.org/10.1155/2024/6624083>
- Khiari, Z., Tebsi, Y., Ben Ali, J., Romdhane, M.S., & Laroche, C. (2022). Sustainable upcycling of fisheries and aquaculture waste using cold-adapted enzymes. *Frontiers in Nutrition*, 9, 875697. <https://doi.org/10.3389/fnut.2022.875697>
- Membranes Editorial Board. (2011). Membrane bioreactor technology for the development of bioactive peptides and oligosaccharides. *Membranes*, 2(4), 756–772. <https://doi.org/10.3390/membranes2040756>
- Nikoo, M., Regenstein, J.M., & Yasemi, M. (2023). Protein hydrolysates from fishery processing by-products: Production, characteristics, food applications, and challenges. *Foods*, 12(24), 4470. <https://doi.org/10.3390/foods12244470>
- Türkten, H., Bostan, G., & Karaman, Y. (2023). Reducing food loss and waste in the fish value chain: A study on environmental efficiency in Türkiye. *Corporate Social Responsibility and Environmental Management*, 30(2), 1245–1260. <https://doi.org/10.1002/csr.70008>
- Venugopal, V. (2021). Valorization of seafood processing discards and byproducts. *Frontiers in Sustainable Food Systems*, 5, 611835. <https://doi.org/10.3389/fsufs.2021.611835>
- Venugopal, V. (2022). Green processing of seafood waste biomass towards blue economy. *Current Research in Environmental Sustainability*, 4, 100141. <https://doi.org/10.1016/j.crsust.2022.100141>
- Xia, F.L.W., Mu, X.Y., Li, Y., & Zhang, H.Y. (2024). Turning waste into value: Extraction and effective utilization of seafood by-products. *Marine Life Science & Technology*, 6, 123–145. <https://doi.org/10.1016/j.marlifesci.2024.01.002>
- Ramachandra, S., Liyanage, R., Kumarasinghe, U. and Alahakoon, A.U., 2025. Environmental Sustainability through Insect Protein: Potential Feed and Food Applications in Sri Lanka. *Biological Innovations for Environmental Sustainability*, p.62.
- Islam, J., Yap, E.E.S., Krongpong, L., Toppe, J. and Peñarubia, O.R., 2021. Fish waste management: Assessment on potential production and utilization of fish silage in Bangladesh, Philippines and Thailand. *Food & Agriculture Org.*.
- Paranamana, G.P., Herath, H.M.R.P., Kularatne, M.G., Kanchana, R.A.C. and Ekanayake, D.N.B., 2025. Gender-specific roles and opportunities in the value chain: A case study of culture-based fisheries in selected Sri Lankan reservoirs. *Journal of Multidisciplinary & Translational Research*, 9(2).
- Ahamed Rifath, M. R., Mohamed Thariq, M. G., & Mohamed Gazzaly. (2023). Fish waste to fish meal: Potential, sustainability and emerging issues related to micro plastics and regulations. *Journal of Fisheries and Environment*, 47(2), 1–18.

- Espinales, C., Díaz Enríquez, M., Arellano Menéndez, L., & Venugopal, V. (2023). Collagen, protein hydrolysates and chitin from by-products of fish and seafood processing: Extraction, characterization, and applications. *Heliyon*, 9(3), e14408. <https://doi.org/10.1016/j.heliyon.2023.e14408>
- Food and Agriculture Organization of the United Nations. (2018). Circular economy and the fish value chain [Fact sheet]. Retrieved from <https://www.fao.org/flw-in-fish-value-chains>
- Food and Agriculture Organization of the United Nations. (2018). Food loss and waste in fish value chains: A review of the literature [Technical Report]. Retrieved from <https://www.fao.org/3/ca0352en/CA0352EN.pdf>
- Food and Agriculture Organization of the United Nations. (2021). Can the circular economy reduce waste in the fish value chain? [Discussion paper]. Retrieved from <https://www.fao.org/flw-in-fish-value-chains>
- Jayathilake, J. M. N. J. (2020, July 22). Potential products from fishing industry waste: Green solutions. *Sri Lanka Guardian*. Retrieved from <http://www.srilankaguardian.org>
- Ministry of Fisheries, Government of Sri Lanka. (2019). Fisheries and aquaculture strategic policy framework and action plan.
- Seafish. (2025). Driving a circular economy in seafood supply chains [Industry report]. Retrieved from <https://www.seafish.org>
- Venugopal, V. (2021). Valorization of seafood processing discards and byproducts. *Frontiers in Sustainable Food Systems*, 5, 611835. <https://doi.org/10.3389/fsufs.2021.611835>
- Kolawole, A.A. and Mustapha, A.K., 2023. Farmed fish feeds: use of non-conventional feed as fishmeal replacement in Nigeria. *Journal of Applied Sciences and Environmental Management*, 27(7), pp.1387-1398.
- Jayaweera, D.D., Dargentolle, C. and Kuganathan, S., 2024. Nutritional composition and fatty acid profile of Yellowfin Tuna (*Thunnus albacares*) by-products in Sri Lanka. *Vingnanam Journal of Science*, 19(1).
- Rahman, M.H., Alam, M.A., Flura, M.M., Mely, S.S., Sultana, S. and Islam, M.R., 2023. A Review on the Current Status and Emerging Trends in the Utilization of Fish Feed Additives for Sustainable Production of *Oreochromis Niloticus*. *Am. J. Aquac. Anim. Sci*, 2(2), pp.26-37.
- DASANAYAKE, A.D.S.L., 2022. PRODUCTION OF A LIQUID FERTILIZER USING SEA TRASH FISH AND MOLASSES.
- Badoni, P., Nazir, I., Aier, M., Maity, P.B., Samanta, S. and Das, A., 2021. Significant role of fish nutrients with special emphasis to essential fatty acid in human nutrition. *Int. J. Curr. Microbiol. Appl. Sci*, 10, pp.2034-2046.
- Jayasekara, I.G.R.I., Wijekoon, A.P. and Somaratne, G.M., 2022. Contribution of dried fish to food and nutrition security in Sri Lanka: A review. *The Journal of Nutrition and Food Sciences*, 1(1).
- Cooney, R., de Sousa, D.B., Fernández-Ríos, A., Mellett, S., Rowan, N., Morse, A.P., Hayes, M., Laso, J., Regueiro, L., Wan, A.H. and Clifford, E., 2023. A circular economy framework for seafood waste valorisation to meet challenges and opportunities for intensive production and sustainability. *Journal of Cleaner Production*, 392, p.136283.



ICRES26_041

A COMPARATIVE SUSTAINABILITY ASSESSMENT OF COSMETIC BOTTLE DESIGNS

P.M.M.P Thennakoon^{1*}, J.R Gamage², H.P Karunathilake²

¹*Department of Mechanical Engineering, University of Moratuwa, Sri Lanka.*

²*Department of Energy and Mechanical Engineering, University of Aalto, Finland.*

**Correspondence E-mail: maleeshap@uom.lk, TP: +94711974359*

Abstract: Resource efficiency is a forward step toward sustainability. Still, there are few studies on resource efficiency and life-cycle assessments of cosmetic containers with varying volumetric capacities. Some smaller container designs are encouraged to increase purchasing frequency, which can lead to environmental drawbacks. Material efficiency and environmental performance are crucial for the development of sustainable packaging. This study aims to conduct a comparative life-cycle assessment and propose a packaging efficiency index (PEI) for cosmetic containers with varying volumetric capacities. Three types of commercially available high-density polyethylene (HDPE) flip-top cap bottles are examined. Material efficiency was quantified using the PEI, defined as the ratio of packaging weight to product weight. In addition, a cradle-to-gate LCA was conducted using a functional unit of packaging required to deliver one Liter of content (moisturizer). Global warming potential (GWP) was selected as the primary impact indicator. Life cycle inventory data for plastic production were obtained from published literature sources. The results reveal substantial variation in packaging performance among the assessed designs, with PEI values ranging from 5.4 to 8.2. A higher packaging efficiency index and a lower GWP indicate potential benefits for logistics on a per-functional-unit basis compared to lower-volume containers. Sensitivity analysis confirms that GWP scales linearly with packaging weight (with ± 10 -20% variation), validating the robustness of the findings. Overall, findings demonstrate that integrating a weight-based efficiency indicator into LCA provides a practical and robust approach to the sustainability assessment of cosmetic packaging. This combined approach supports packaging designers in making decisions that conserve materials and reduce global warming potential, both of which are critical sustainability considerations.

Keywords: Sustainability; Life cycle assessment; Material efficiency; Global warming potential

1. Introduction

The circular economy is a forefront topic in sustainability in the packaging sector due to its dominance in plastic. Plastics are extensively used across various industries, and packaging covers a large fraction due to their lightweight nature, durability, affordability, and disposability. Global plastic production has surged exponentially from 1.7 million metric tons (Mt) in 1950 to 348 Mt in 2017 (Foschi and Bonoli, 2019). This growth exacerbates environmental challenges, particularly those related to waste. High-density polyethylene (HDPE) is one of the most prevalent waste plastics globally, and 44.71 Mt was generated worldwide in 2019 (Suvari and Gurvardar, 2024). It dominates rigid containers for food, household chemicals, pharmaceuticals, and personal care products, including shampoos, conditioners, creams, and lotions.(Admin, 2024).

The cosmetic packaging industry faces various environmental drawbacks due to the single-use nature of packaging and the mismanagement of waste. This issue is exacerbated by small-volume, high-frequency use of these containers. Brands also encourage consumers to purchase small sizes through marketing. These effects are influenced by common global problems such as global warming, climate change, and marine pollution, given the widespread nature of plastic pollution and its direct and indirect effects. Marine pollution caused by improper plastic disposal has been identified as one of the major environmental issues worldwide. Yearly 8Mt release to the ocean (Springle et al., 2022), and with current trends, the United Nations predicts that the plastic content will outweigh the fish in the ocean by 2050 (Kamalakkannan et al., 2022).

To overcome these issues, many actions have been taken globally. This paper proposes a comparative assessment of the different volumetric capacities of HDPE-based bottles with flip-top caps in the cosmetics industry. Because brands encourage consumers to use smaller-volume capacity containers, this leads to more frequent purchasing. This comparison covers environmental impact assessment and packaging efficiency by weight. This study reveals how packaging size affects environmental impacts, and PEI quantifies packaging efficiency at the point of delivering a functional unit. It assesses bottles' life cycle impacts on a cradle-to-gate basis across 18 impact categories, prioritizing global warming potential (GWP). This study shows the impacts of small-volume containers and compares performance to suggest impact-minimizing approaches for container types. The findings offer guidance for manufacturers and brands to promote eco-friendly solutions for lower-volume capacities while informing policymakers and researchers on advancing sustainability across industries.

2. Literature review

To ensure the authenticity and timeliness of the findings, this study examines recently published books, theses, journal articles, and conference proceedings. In the literature review on HDPE cosmetics, this study examines recently published books, theses, journal papers, and conference proceedings to ensure the results are valid and timely. The most recent results from scholarly publications and trustworthy reports were prioritized in the literature review on the sustainability of HDPE cosmetic packaging, life-cycle assessment, and environmental implications. This approach considers new findings regarding GWP, material efficiency, and regional and global regulations.

2.1 HDPE usage and environmental drawbacks

High-density polyethylene (HDPE) is a widely used thermoplastic in the global packaging sector, particularly for rigid containers in food, household chemicals, pharmaceuticals, and personal care products. (Nayanathara Thattharani Pilapitiya and Ratnayake, 2024). It is characterized by a relatively high density, semi-crystalline structure, and a favourable balance of stiffness, toughness, and processability, which together make it a prime candidate for high-performance packaging applications. (Benham and McDaniel, 2005). Led to its extensive use in extrusion and blow moulding of bottles, jars, and other rigid containers, where uniform wall thickness and dimensional stability are required. Typical applications include packaging for shampoos, conditioners, creams, lotions, detergents, and other household and cosmetic products. Positioning HDPE as one of the dominant materials for personal care and pharmaceutical bottles(Admin, 2024).

In addition to its functional performance, HDPE is increasingly discussed in the context of the circular economy and life cycle thinking, because despite HDPE plastic being one of the most prevalent waste plastics globally (Suari & Gurvardar, 2024). In marine environments, HDPE degradation occurs through a combination of physical, chemical, and biological processes that may interact throughout the exposure period. Physical factors such as ultraviolet (UV) radiation, wave action, and mechanical stress cause HDPE to fragment into smaller particles, known as microplastics (Kögel et al., 2020a). These microplastics then undergo further chemical changes due to exposure to UV light, a process called photo-oxidation, in which UV radiation breaks down polymer bonds (Lourmpas et al., 2024) and generates nano plastics. which infiltrate aquatic food chains, threatening human food security and health (Kögel et al., 2020). Because of these issues, HDPE is encouraged to be recycled.

The effects of plastic micro- and nano plastics have been shown to disrupt biological functions at the organizational and cellular levels. (Law, 2017; Reimonn et al., 2019). The prevalence of microplastics (MP) is difficult to exaggerate. MP has been found in samples collected from depths of 1000 to more than 5000 meters in the ocean. (Van Cauwenberghe et al., 2013), as well as in the Laurentian Great Lakes of the US (Eriksen et al., 2013), freshwater lakes in Mongolia (Free et al., 2014), and sediment samples from the river Rhine in Germany (Mani et al., 2019). Therefore, plastic pollution comes as one of the main threats to human health and the ecosystem. Although many attempts are being made to reduce plastic mismanagement and waste reduction globally.

Mechanical recycling of post-consumer HDPE has been shown to provide significant environmental benefits relative to producing virgin resin, including substantial reductions in non-renewable energy demand and greenhouse gas emissions. (Istrate et al., 2021). Multiple recycling loops of HDPE can significantly reduce total climate change and resource depletion when efficient collection and recycling systems are in place, according to life cycle assessment (LCA) research. Additionally, reduce impacts compared with linear, single-use scenarios dominated by landfilling or incineration. Consequently, HDPE packaging is often highlighted as a promising candidate for closed-loop systems. In industries such as cosmetics and personal care, performance-driven design solutions are used to reduce material consumption, improve recyclability, and reduce the environmental impact of plastic packaging. (Gandhi et al., 2021).

2.2 Small-sized packaging influences the consumers' buying behaviour

In the beauty industry, packaging significantly influences customers' purchasing decisions. It combines information, functionality, and aesthetic appeal to influence attitudes, perceptions, and purchases (Sitopu and Firdaus, 2024). Decisions are further influenced by small container sizes that satisfy requirements such as travel portability. helps prevent large bottles that violate airplane liquid regulations and accommodates hectic schedules with precise portion management (Mohamed et al., 2018, Yang, 2024). Mobile customers on holiday or business excursions who require portable solutions to maintain skincare and cosmetics routines effortlessly may find this appealing.

For premium brands, small packaging signals luxury and exclusivity through elegant designs. Boosting perceived quality and standing out in competitive markets (Dubey, 2025). It serves practical needs like portability and precise dosing while evoking high-end aesthetics, making it essential in modern cosmetic paradigms. (Yang, 2024).

In price-sensitive markets like India, South America, Europe, the Middle East, and Africa, small sizes win on affordability, hitting key price points to drive broader reach. Smaller formats traditionally dominate impulse buys and are expanding into premium segments in the Americas, attracting budget-aware yet quality-focused buyers. (Wong, 2024). Thus, small packaging expands the consumer base but generates higher waste volumes due to increased usage and disposal rates.

2.5 LCA studies on cosmetic containers

The environmental profile of HDPE is benchmarked against existing life cycle assessment (LCA) studies on cosmetic containers, which is consistent with its widespread use in rigid bottles and jars for creams and lotions. A cradle-to-grave multi-attribute life cycle assessment (LCA) has been conducted on cosmetic compacts using Simapro. A study was conducted comparing virgin and post-consumer-recycled (PCR) ABS, PP, PET, PLA, and wood-polymer composites. That was revealed, PP demonstrated approximately 46% lower impacts than HDPE/ABS baselines, and 100% PCR reduced burdens by 42–60% (Vassallo and Refalo, 2024).

Another study assessed a 50 ml cosmetic jar via LCA, finding that recycled PET (rPET) had the lowest impacts across categories compared to virgin PP, PET, and glass. However, recycling burdens, such as water use, were higher. (Rudolf et al., 2024). The PCR content and mineral fillers reduced cradle-to-gate impacts by up to 29% across most categories, according to the evaluation of cosmetic tubes made from HDPE & LDPE. (Cubas et al., 2022).

2.5 Policy on waste mitigation

89% of Sri Lanka's annual plastic waste is inadequately managed, and its per capita value is 10.5 kg, approximately 2 kg lower than the global average of 12.5 kg. Human health and the environment are harmed by this high rate of mismanagement, which causes pollution in rivers, seas, and landfills. The "National Action Plan on Plastic Waste Management 2021–2030" establishes specific objectives to reduce problematic single-use plastics by 80% and achieve 80% collection and recycling of all plastic trash by 2025 in order to reduce pollution (Cooray, 2021). Key support comes from the Ministry of Environment's "National Environmental (Plastic Material Identification Standards) Regulations No. 01 of 2021." This rule helps identify plastic types in products, making it easier to sort and recycle at factories and homes, thus cutting waste from the start (Balachandra and Abeysekara, 2024). In April 2025, the United Nations Development Programme (UNDP) and The Coca-Cola Foundation launched a \$1.1 million project. It builds better waste systems across seven areas in the Colombo District, improving collection, recycling, and safe disposal to keep plastics out of nature. (Srikanth, 2025).

Sri Lanka's efforts align with international initiatives to reduce plastic waste through circular economy concepts, recycling, and reuse rather than discarding. Plastic packaging waste (PPW), which accounts for 40% of all plastics produced but 60% of waste, is a focus of the European Union. EU regulations encourage less new plastic waste and increased recycling. (Brouwer et al., 2020). The United States Environmental Protection Agency (US-EPA) encourages consumers to buy packaged products with a lower environmental impact than other products that serve the same purpose. (Fresán et al., 2019). Together, these steps help Sri Lanka tackle local problems and promote sustainable packaging, like for cosmetics, leading to less waste and better resource use.

3. Methodology

3.1 Market survey

One of the major HDPE bottle manufacturers, supplying a significant portion of the market demand, was interviewed to gather essential information. Simultaneously, lifecycle inventory data were obtained from product datasheets.

Due to the proliferation of manufacturers and brands, the market offers a wide variety of HDPE bottles and flip-top cap designs. These bottles also come in a range of sizes to accommodate varying amounts of cosmetic products. For this study, one bottle-and-cap design was selected, all of which carried the same product but different product volumes. Selection criteria included market availability, ability to deliver the same product, ease of data access, high sales rates, and customer demand for single-use packaging designs. The analysis focuses on the physical and environmental performance of each bottle size.

The collected data for these three bottle sizes are presented in the accompanying Table 01. Weights were measured for empty containers at the manufacturing site before filling. Three empty containers for each volume were weighed to determine average weights, using a Citizen electronic precision balance. This procedure was applied separately to every bottle body and cap (standard deviations <2%). Manufacturer process datasheets were used to determine the energy consumption for injection molding (2.5 MJ of electricity/kg HDPE), and country-mix electricity was used, with ecoinvent v3 averages. granulate production data ("polyethylene, HD, granulate {GLO}| market for"), which represented global market mixes. Transport assumptions included resin delivery to the country via a freight sea transoceanic ship, with "sea distance.org" used to measure the ocean distance between the harbours.

Table 1: container weight measurements

Bottle Types	Containing amount of the product (ml)	Weight of the bottle (g)	Weight of the body (g)	Weight of the cap (g)
Type 1	40	9.16	5.67	3.49
Type 2	100	19.34	14.45	4.89
Type 3	200	28.18	19.77	8.41

3.2 Packaging efficiency index calculation

The amount of packaging material affects the packaging weight. That plays a major role in environmental impacts and the logistic handling. Packaging efficiency (PE) was defined as the ratio of the packaging weight to the product weight. (Klein et al., 2025) . This approach, known as the packaging-to-product ratio, can be expressed as Packaging Efficiency. (Brouwer and Velzen, 2023). Proposing the terminology: Packaging Efficiency (PE).

PE = Packaging Efficiency (dimensionless)

W_e = Weight of empty packaging (g)

W_p = Weight of product (g)

$$PE = \frac{w_e}{(w_e + w_p)} \times 100 \quad (1)$$

This equation yields results where lower values indicate better efficiency. However, to avoid confusion with the term "efficiency" and create a higher-is-better index, the reciprocal is taken and multiplied by 100. To create an intuitive "higher-is-better" index, propose a term for the Packaging Efficiency Index (PEI):

$$PEI = \frac{100}{PE} \quad (2)$$

3.3 Environmental impact comparison

According to ISO 14040/14044 standards, life cycle impacts were assessed using SimaPro 9.3.0.3 in conjunction with the ecoinvent database and the ReCiPe Midpoint (H) approach. The Midpoint approach was selected for its capacity to aggregate results into relatable, less technically complex indicators, facilitating effective public communication of packaging sustainability.(Huijbregts et al., 2017).

GWP was adopted as a key parameter for evaluating the three volumetric capacities of the bottle options. Numerous prior studies in environmental sustainability assessments have leveraged GWP as a benchmark for comparing alternatives, given its robustness and policy relevance in ISO 14067(Lynch et al., 2020). GWP was prioritized as the representative impact category, reflecting the global imperative for climate change mitigation and the intensifying regulatory emphasis on low-carbon packaging designs in the cosmetics sector. Numerous studies have employed GWP to evaluate the environmental

impacts of various alternatives. Previous literature identifies six main criteria for selecting a suitable eco-impact indicator. They are representative of environmental conditions, simple, responsive to environmental and human activities, able to provide quantifiable value for impact assessment, technically available, and grounded in international standards. (Persson, 2001).

The functional unit is defined as "the packaging required to deliver one Liter volume of content (moisturizer)." System boundaries encompass raw material extraction through bottle production completion, as illustrated by the shaded area bounded by a dashed line in Figure 1. A cradle-to-gate scope was applied for inventory development and impact assessment across all bottles. Aligning with industry standards for HDPE packaging, LCAs, and enabling targeted identification of production-phase hotspots.

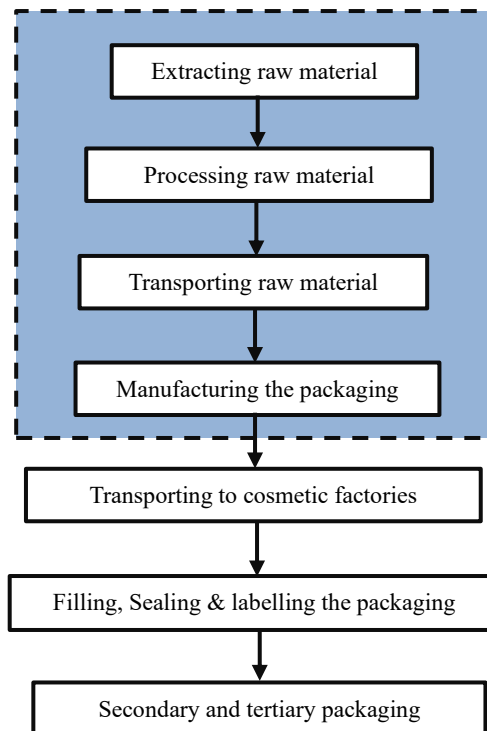


Figure 1: System boundary: The shaded area separated by a dashed line is the one considered for this study

4. Analysis and Results

4.1 Comparison of PEI performance

Table 2 presents the Packaging Efficiency Index (PEI) for bottles with different volumetric capacities, along with the weight of each bottle body and cap. All designs contain the same product, enabling direct comparability of material efficiency across flip-top cap bottles with different size configurations.

Table 2: Packaging efficiency and packaging efficiency index

Containing amount of the product (ml)	Weight of filled bottle (g)	Weight of empty bottle (g)	Packaging Efficiency	Packaging Efficiency Index
40	49.81	9.16	18.389	5.437
100	123.92	19.34	15.606	6.407
200	231.18	28.18	12.189	8.203

Table 3: Packaging material allocation

Bottle types	Containing amount (ml)	Weight of the body (%)	Weight of the lid (%)
Type 1	40	61.89	38.10
Type 2	100	74.71	25.28
Type 3	200	70.15	29.84

4.2 Environmental impact assessment

Table 4 summarizes the ReCiPe 2016 midpoint (H) impacts per 1 L functional unit for 40 ml, 100 ml, and 200 ml HDPE flip-top cap cosmetic bottles. Dominant categories include global warming, fossil resource scarcity, freshwater ecotoxicity, and water consumption, while stratospheric ozone depletion and ionizing radiation contribute marginally.

Across nearly all indicators, the 40 ml bottle exhibits the highest impacts per functional unit. This trend stems from greater material demand, manufacturing operations, and emissions when smaller volumes are required to deliver the same 1 L of product. Due to higher material consumption, processing, and emissions, the 40 ml bottle has the greatest impact per liter. In addition to lower packaging mass and fewer units required, the 200 ml size has the lowest global warming potential (kg CO₂ equivalent) among the sizes as capacity increases (Figure 2). Larger volume-to-surface ratios improve material efficiency and lessen production burdens, which is consistent with LCA behavior. Due to decreased polymer use and upstream extraction, resource categories, including mineral and fossil scarcity, follow this drop. Because of the increased polymer and energy inputs, toxicity indicators penalize the 40 ml variant even though it differs less. In general, lighter, higher-volume, or refillable designs for sustainable packaging are supported by the superior environmental performance of larger bottles.

Table 4: Environmental Impact Assessment in ReCiPe midpoint(H) for one Liter functional unit

Impact category	Unit	40 ml bottle	100 ml bottle	200ml bottle
Global warming	kg CO ₂ eq	0.830352	0.701268	0.510903
Stratospheric ozone depletion	kg CFC11 eq	1.44E-07	1.22E-07	8.88E-08
Ionizing radiation	kBq Co-60 eq	0.024137	0.020384	0.014851
Ozone formation, Human health	kg NO _x eq	0.001713	0.001447	0.001054
Fine particulate matter formation	kg PM _{2.5} eq	0.001142	0.000964	0.000703
Ozone formation, Terrestrial ecosystems	kg NO _x eq	0.001846	0.001559	0.001136
Terrestrial acidification	kg SO ₂ eq	0.002402	0.002028	0.001478
Freshwater eutrophication	kg P eq	0.000153	0.000129	9.42E-05
Marine eutrophication	kg N eq	1.09E-05	9.17E-06	6.68E-06
Terrestrial ecotoxicity	kg 1,4-DCB	0.315955	0.266831	0.194399
Freshwater ecotoxicity	kg 1,4-DCB	0.007885	0.006659	0.004851
Marine ecotoxicity	kg 1,4-DCB	0.010803	0.009123	0.006647
Human carcinogenic toxicity	kg 1,4-DCB	0.021911	0.018504	0.013481
Human non-carcinogenic toxicity	kg 1,4-DCB	0.186389	0.157411	0.114681
Land use	m ² a crop eq	0.015186	0.012825	0.009343
Mineral resource scarcity	kg Cu eq	0.000583	0.000493	0.000359
Fossil resource scarcity	kg oil eq	0.466098	0.39364	0.286783
Water consumption	m ³	0.005695	0.00481	0.003504

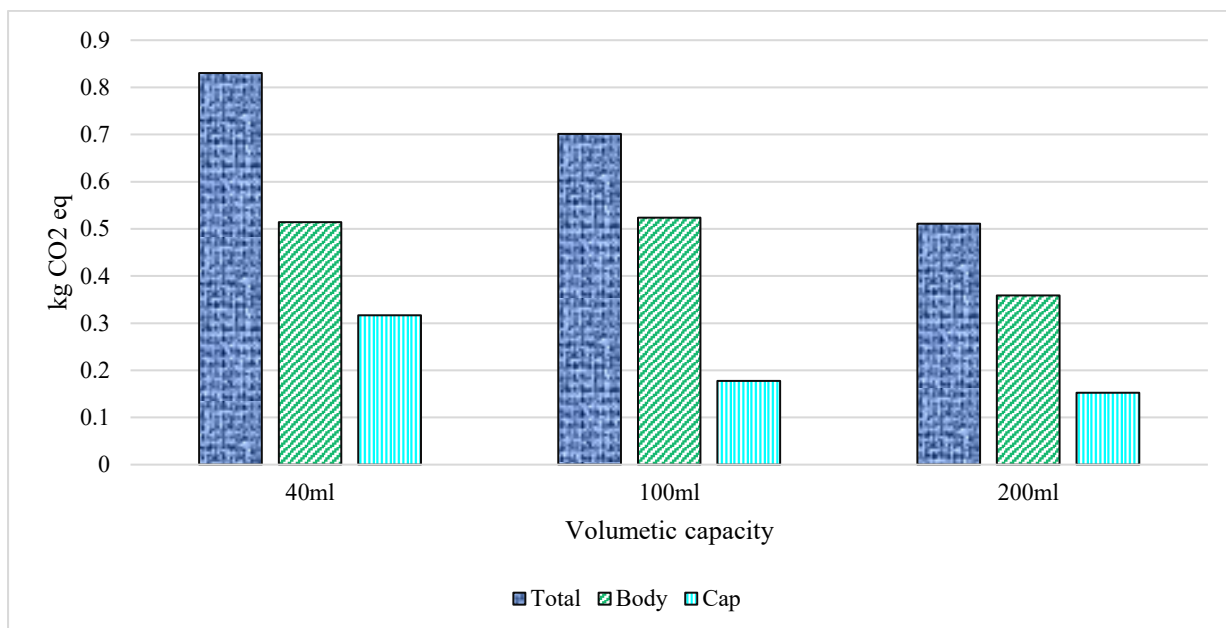


Figure 2: GWP of each bottle delivering one Liter functional unit

4.2 Sensitivity analysis

Sensitivity analysis was performed to assess the validity of the LCA findings by varying bottle weight and emission parameters. Injection molding manufacturing tolerances usually result in weight variations of $\pm 10\text{-}20\%$ because of material batch discrepancies, mold wear, and process oscillations. For each bottle size, SimaPro simulations were run in three scenarios: base case (measured weights), $\pm 10\%$ increases and decreases in weight, and $\pm 20\%$ increases and decreases in weight.

Table 5: Weight-based sensitivity of the GWP indicator

Bottle Type	Base Weight (g)	Weight fluctuation Scenario Type	GWP (kg CO ₂ eq)
40ml	9.16	-20%	0.664282
		-10%	0.747317
		Base	0.830352
		10%	0.913387
		20%	0.996423
100ml	19.34	-20%	0.561014
		-10%	0.631141
		Base	0.701268
		10%	0.771395
		20%	0.841521
200ml	28.18	-20%	0.408722
		-10%	0.459812
		Base	0.510903
		10%	0.561993
		20%	0.613083

GWP was used as the initial indicator for this study, and Table 5 shows the variation in results with weight sensitivity. GWP scales linearly with packaging weight across all bottle sizes, demonstrating that material mass is the dominant impact driver (approximately 75-80% of total GWP). A $\pm 10\%$ weight variation produces a $\pm 10\%$ GWP change, while $\pm 20\%$ weight variation yields $\pm 20\%$ GWP variation.

Critically, the relative performance ranking remains unchanged across all scenarios: the 40 ml bottle consistently exhibits the highest GWP per functional unit, followed by 100 ml, with 200 ml demonstrating the lowest climate impact. Similar linear relationships were observed for fossil resource scarcity (kg oil eq) and ecotoxicity indicators, confirming that conclusions regarding optimal container sizing are robust to manufacturing variability.

5. Discussion

Literature surveys highlight key considerations for minimizing environmental impacts across the full life cycle of HDPE packaging. In the local cosmetic market, HDPE flip-top cap bottle varieties exhibit diverse characteristics. Aesthetic designs are primarily driven by branding and marketing priorities that often compromise environmental sustainability. Effective administrative guidance and stakeholder collaboration in sharing environmental responsibilities are essential for developing low-impact packaging. Strengthening local infrastructure, particularly through adequate PP recycling facilities and measures to minimize leakage from closed-loop life cycles, will bolster reverse supply chain efficiency. Long-term strategic plans should emphasize public awareness campaigns on proper disposal methods.

As all designs are commercially available in the local market, where sales rely heavily on brand and other factors, aesthetic appeal significantly influences consumer preferences. This study recommends maintaining visual appeal while prioritizing material reduction during manufacturing to enhance PEI value and encourage consumers to purchase more products. Such optimizations can differentiate products as eco-friendly alternatives, appealing to consumers by minimizing their impact relative to higher-material-consumption containers. The volume of HDPE flip-top cap bottles and environmental impact per functional unit (1 L moisturizer) are clearly inversely correlated, according to this study. Because of its optimal product-to-packaging ratio, which reduces material per liter, the 200 ml container achieves the maximum Packaging Efficiency Index (PEI) of 8.203 and the lowest GWP of 0.511 kg CO₂ eq/L. It is a 38% reduction compared to the 40 ml (0.830 kg CO₂ eq/L). Larger container forms perform better than smaller ones across all ReCiPe Midpoint (H) categories, with the main loads coming from water use, freshwater ecotoxicity, fossil shortages, and global warming.

According to previous HDPE packaging LCAs, the manufacture of HDPE resin accounts for 75–80% of impacts, followed by injection molding (15–18%) and shipping (5–7%). The high cap-to-body ratio (38.1%) of the 40 ml design exacerbates the excessive contribution of caps (30–40% of molding energy despite 25–38% mass). Sensitivity analysis ($\pm 20\%$ weight variation) validates material reduction as the primary sustainability lever and supports robust rankings, as GWP scales linearly with mass.

These findings support life cycle assessment (LCA) principles, with larger volumes, upstream burdens (transport, molding, and resin) are effectively spread, offsetting marketing-driven small-size preferences that increase waste. To reduce environmental impact without sacrificing functionality and increase market appeal through eco-labeling in Sri Lanka's cosmetics industry, designers should prioritize cap simplification, thinner walls, and 100–200 ml shifts or refills. By encouraging stakeholder cooperation and investing in recycling infrastructure, policymakers can use these results to improve the National Action Plan on Plastic Waste Management.

As a limitation of the study, the cradle-to-gate scope relies on worldwide ecoinvent v3 averages from a single facility, excluding use/end-of-life, labels, inks, and Sri Lanka-specific energy/transport data. For generalizability, brand details are left out of the analysis, which covers a single flip-top design spanning three volumes.

As the upcoming studies suggest, extend to cradle-to-grave evaluations using regional data, Monte Carlo uncertainty analysis, recycling scenarios, and multi-design/material comparisons (rHDPE, bio-PE). To increase transparency and applicability, add branded components and additional LCI tables.

6. Conclusion

This study conducted a comparative cradle-to-gate LCA and PEI assessment of three HDPE flip-top cap cosmetic bottles (40 ml, 100 ml, and 200 ml), revealing significant differences in environmental performance and material efficiency. Due to improved volume-to-surface ratios, the 200 ml variant demonstrated superior PEI (8.203) and the lowest GWP (0.511 kg CO₂ eq/L), a 38% decrease compared to the 40 ml (0.830 kg CO₂ eq/L). These results confirmed an inverse relationship between container volume and environmental burdens across 18 ReCiPe Midpoint (H) categories. These results demonstrate that smaller-volume designs increase resource requirements and GWP per functional unit (1 L moisturizer), exacerbating plastic waste in cosmetics packaging, despite consumer preference for portability and affordability.

To improve sustainability and market differentiation, cosmetic firms should choose 100–200 ml packaging, streamlined lids, and reduced material use. These insights can be used by Sri Lankan authorities to improve the National Action Plan on Plastic Waste Management through eco-design guidelines and recycling incentives. Cradle-to-grave scopes, regional data, multi-design/material studies (such as rHDPE), and uncertainty propagation in accordance with ISO 14044 should all be included in future work.

Acknowledgements

The authors gratefully acknowledge the University of Moratuwa for financial support through the SENET Research Grant SRC/LT/2020/2029. Further, the authors are grateful to HDPE Bottle Manufacture for generously sharing proprietary production data essential to this life cycle assessment.

References

- Admin, S., 2024. HDPE: Properties, Applications, and Manufacturing Process. Song Minh Plastic Corporation. URL <https://songminh.vn/en/hdpe-properties-applications-and-manufacturing-process/> (accessed 2.2.26).
- Balachandra, B.A.K.S., Abeysekara, T.B. (2024). Legal Framework of Plastic Packaging and Labelling in Sri Lanka: A Comparative Analysis. *KDU J. Multidisc. Stud.* 6, 5–16. <https://doi.org/10.4038/kjms.v6i1.104>
- Benham, E., McDaniel, M. (2005). Polyethylene, High Density, in: Kirk-Othmer (Ed.), *Kirk-Othmer Encyclopedia of Chemical Technology*. Wiley. <https://doi.org/10.1002/0471238961.0809070811091919.a01.pub2>
- Brouwer, M., Velzen, U.T. van, (2023). Multi-dimensional sustainability assessment of product-packaging combinations : MuDiSa: a calculation tool to assess the sustainability of product-packaging combinations in multiple dimensions of sustainability. <https://doi.org/10.18174/633072>
- Brouwer, M.T., Thoden Van Velzen, E.U., Ragaert, K., Ten Klooster, R., (2020). Technical Limits in Circularity for Plastic Packages. *Sustainability* 12. <https://doi.org/10.3390/su122310021>
- Cooray, N. (2021). National action plan on plastic waste management, 2021-2030, First edition. ed. Ministry of Environment, Sri Lanka, Battaramulla, Sri Lanka.
- Cubas, A.L.V., Bianchet, R.T., Reis, I.M.A.S.D., Gouveia, I.C. (2022). Plastics and Microplastics in the Cosmetic Industry: Aggregating Sustainable Actions Aimed at Alignment and Interaction with UN Sustainable Development Goals. *Polymers* 14, 4576. <https://doi.org/10.3390/polym14214576>
- Dubey, Y. (2025). The Power of Less: Investigating the Impact of Minimalist Branding on Consumer Perception and Purchase Behavior in the Cosmetic Industry. *ISJEM* 04, 1–9. <https://doi.org/10.55041/ISJEM04099>
- Eriksen, M., Mason, S., Wilson, S., Box, C., Zellers, A., Edwards, W., Farley, H., Amato, S. (2013). Microplastic pollution in the surface waters of the Laurentian Great Lakes. *Marine Pollution Bulletin* 77, 177–182. <https://doi.org/10.1016/j.marpolbul.2013.10.007>
- Foschi, E., Bonoli, A., (2019). The Commitment of the Packaging Industry in the Framework of the European Strategy for Plastics in a Circular Economy. *Administrative Sciences* 9, 18. <https://doi.org/10.3390/admsci9010018>
- Free, C.M., Jensen, O.P., Mason, S.A., Eriksen, M., Williamson, N.J., Boldgiv, B., 2014. High levels of microplastic pollution in a large, remote, mountain lake. *Marine Pollution Bulletin* 85, 156–163. <https://doi.org/10.1016/j.marpolbul.2014.06.001>
- Fresán, U., Errendal, S., Craig, W.J., Sabaté, J. (2019). Does the size matter? A comparative analysis of the environmental impact of several packaged foods. *Science of The Total Environment* 687, 369–379. <https://doi.org/10.1016/j.scitotenv.2019.06.109>
- Gandhi, N., Farfaras, N., Wang, N.-H., Chen, W.-T. (2021). Life Cycle Assessment of Recycling High-Density Polyethylene Plastic Waste. *JRM* 9, 1463–1483. <https://doi.org/10.32604/jrm.2021.015529>
- Huijbregts, M.A.J., Steinmann, Z.J.N., Elshout, P.M.F., Stam, G., Verones, F., Vieira, M., Zijp, M., Hollander, A., Van Zelm, R., (2017). ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level. *Int J Life Cycle Assess* 22, 138–147. <https://doi.org/10.1007/s11367-016-1246-y>
- Istrate, I.-R., Juan, R., Martín-Gamboa, M., Domínguez, C., García-Muñoz, R.A., Dufour, J., (2021). Environmental life cycle assessment of the incorporation of recycled high-density polyethylene into polyethylene pipe grade resins. *Journal of Cleaner Production* 319, 128580. <https://doi.org/10.1016/j.jclepro.2021.128580>
- Kamalakkannan, S., Abeynayaka, A., Kulatunga, A.K., Singh, R.K., Tatsuno, M., Gamaralalage, P.J.D. (2022). Life Cycle Assessment of Selected Single-Use Plastic Products towards Evidence-Based Policy Recommendations in Sri Lanka. *Sustainability* 14. <https://doi.org/10.3390/su142114170>

- Klein, M., Oleynikova, A., Neumair, C., Tacker, M., Apprich, S. (2025). Assessment of Sustainability Indicators for Cosmetic Product Packaging in the DACH Region. *Cosmetics* 12, 56. <https://doi.org/10.3390/cosmetics12020056>
- Kögel, T., Bjørøy, Ø., Toto, B., Bienfait, A.M., Sanden, M. (2020b). Micro- and nanoplastic toxicity on aquatic life: Determining factors. *Science of The Total Environment* 709. <https://doi.org/10.1016/j.scitotenv.2019.136050>
- Law, K.L., 2017. Plastics in the Marine Environment. *Annu. Rev. Mar. Sci.* 9, 205–229. <https://doi.org/10.1146/annurev-marine-010816-060409>
- Lynch, J., Cain, M., Pierrehumbert, R., Allen, M. (2020). Demonstrating GWP*: a means of reporting warming-equivalent emissions that captures the contrasting impacts of short- and long-lived climate pollutants. *Environ. Res. Lett.* 15, 044023. <https://doi.org/10.1088/1748-9326/ab6d7e>
- Mani, T., Primpke, S., Lorenz, C., Gerdts, G., Burkhardt-Holm, P., (2019). Microplastic Pollution in Benthic Midstream Sediments of the Rhine River. *Environ. Sci. Technol.* 53, 6053–6062. <https://doi.org/10.1021/acs.est.9b01363>
- Mohamed, N.B.A., Medina, I.G., Romo, Z.G. (2018). The Effect of Cosmetics Packaging Design on Consumers' Purchase Decisions. *Indian Journal of Marketing* 48. <https://doi.org/10.17010/ijom/2018/v48/i12/139556>
- Nayanathara Thathsarani Pilapitiya, P.G.C., Ratnayake, A.S. (2024). The world of plastic waste: A review. *Cleaner Materials* 11, 100220. <https://doi.org/10.1016/j.clema.2024.100220>
- Persson, J.-G. (2001). Eco-indicators in product development. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture* 215, 627–635. <https://doi.org/10.1243/0954405011518566>
- Reimonn, G., Lu, T., Gandhi, N., Chen, W.-T. (2019). Review of Microplastic Pollution in the Environment and Emerging Recycling Solutions. *Journal of Renewable Materials* 7, 1251–1268. <https://doi.org/10.32604/jrm.2019.08055>
- Rudolf, R., Majerič, P., Pintarič, Z.N., Horvat, A., Krajnc, D., 2024. Life Cycle Assessment (LCA) of the Impact on the Environment of a Cosmetic Cream with Gold Nanoparticles and Hydroxylated Fullerene Ingredients. *Applied Sciences* 14, 11625. <https://doi.org/10.3390/app142411625>
- Sitopu, J.W., Firdaus, A., (2024). Analyzing the Impact of Packaging Design on Consumer Purchasing Decisions in the Cosmetics Industry. *JEMBUT* 3, 1–8. <https://doi.org/10.35335/jembut.v3i1.220>
- Springle, N., Li, B., Soma, T., Shulman, T. (2022). The complex role of single-use compostable bioplastic food packaging and foodservice ware in a circular economy: Findings from a social innovation lab. *Sustainable Production and Consumption* 33, 664–673. <https://doi.org/10.1016/j.spc.2022.08.006>
- Srikanth (2025). Plastic pollution in Sri Lanka: Banning of free polyethene bags. *Lankan.org*. URL <https://lankan.org/2025/10/01/battling-the-plastic-pollution-in-sri-lanka/> (accessed 2.5.26).
- Suvari, F., Gurvardar, H. (2024). Revitalizing high-density polyethylene (HDPE) waste: from environmental collection to high-strength hybrid yarns. *Polym. Bull.* 81, 14011–14029. <https://doi.org/10.1007/s00289-024-05367-x>
- Thornton, J.A., Harrison, M.J. (1975). Letter: Duration of action of AH8165. *Br J Anaesth* 47, 1033. <https://doi.org/10.1093/bja/47.9.1033>
- Van Cauwenberghe, L., Vanreusel, A., Mees, J., Janssen, C.R., (2013). Microplastic pollution in deep-sea sediments. *Environmental Pollution* 182, 495–499. <https://doi.org/10.1016/j.envpol.2013.08.013>
- Vassallo, N., Refalo, P., (2024). Reducing the Environmental Impacts of Plastic Cosmetic Packaging: A Multi-Attribute Life Cycle Assessment. *Cosmetics* 11. <https://doi.org/10.3390/cosmetics11020034>
- Wong, A. (2024). When package size matters | Food & Beverage Asia. URL <https://foodbeverageasia.com/when-package-size-matters/> (accessed 2.5.26).

Yang, A. (2024). The Future of Small Container Packaging: Trends, Selection, and Customization. Cosmetic Container Packaging Supplier - Jasmine. URL <https://jasminepackaging.com/the-future-of-small-container-packaging-trends-selection-and-customization/> (accessed 2.5.26).



ICRES

International Conference on
Resource Efficiency Towards Sustainability



Because Tomorrow Matters

Event Partner



Academic Partners

