



The 02nd International Conference on
**UNIVERSITY-INDUSTRY COLLABORATIONS
FOR SUSTAINABLE DEVELOPMENT (ICSD)- 2025**

PROCEEDINGS BOOK

Editors
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THE
COLOMBO
CONFERENCE

The 02nd International Conference on
University-Industry Collaborations for Sustainable Development - (ICSD 2025)
09th - 10th May 2025 | gapHQ, Colombo 07, Sri Lanka

**Proceedings of the 2nd International Conference on University-Industry
Collaborations for Sustainable Development (ICSD 2025)**

9th-10th May 2025, Colombo 07, Sri Lanka

Vision

To create a global platform that inspires and empowers University-Industry collaborations, driving sustainable solutions, innovative technologies, and entrepreneurial strategies for sustainable development

Mission

To facilitate dialogue, knowledge exchange, and partnerships among academia, industry, and policymakers. By integrating cutting-edge research, practical insights, and visionary thinking, the conference seeks to enhance university curricula, strengthen business links, and catalyze the development of innovative sustainable solutions that promote environmental and socio-economic growth

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PREFACE

Welcome to the Second International Conference on University-Industry Collaborations for Sustainable Development (ICSD 2025), also known as The Colombo Conference. This distinguished gathering catalyzes the exchange of cutting-edge ideas, innovative technologies, and entrepreneurial strategies within the realm of agro-industries. With a commitment to fostering sustainability, the conference aims to propel university curricula into new dimensions, fortify business ties, and cultivate a fertile ground for invention, innovation, and entrepreneurship. Contained within this book are the proceedings of research work spanning various sub-specialties, evidence of the diverse and impactful contributions made by scholars and practitioners alike. These proceedings were presented at parallel sessions from May 09th and 10th, 2025 at the gapHQ, Colombo 07, Sri Lanka. We extend our deepest appreciation to our esteemed keynote speakers, whose valuable insights have played a pivotal role in shaping the discourse on University-Industry Collaborations for Sustainable Development. The richness of this compilation is grateful much to the dedication and caliber of the contributing authors, who have presented research papers of exceptional quality. Each paper featured in this book has undergone rigorous scrutiny by a panel of academic and professional experts, individuals distinguished in their respective fields. We express our sincere gratitude to these reviewers for their tireless efforts, which have elevated the scholarly standard of this collection. Acknowledgment is also due to the unwavering support and guidance provided by the local and international advisory committees, as well as the diligent members of the co-chairs committee. Their valuable input has been instrumental in arranging the success of this significant event. We extend our heartfelt thanks to all volunteers who have generously offered their time and expertise, contributing to the seamless execution of the conference. Moreover, we gratefully acknowledge the financial sponsorship generously provided by numerous organizations, whose support has been instrumental in ensuring the achievement of this international conference. It is our earnest hope, as editors, that this proceedings book will serve as a valuable resource for the global research community engaged in studies related to University-Industry Collaborations for Sustainable Development. May the insights shared within these pages inspire and guide future endeavors toward a more sustainable and collaborative future.

Editors

Prof. Ranjith Dissanayake

Dr. Pradeep Gajanayake

The Second International Conference on University-Industry Collaborations for Sustainable Development (ICSD 2025)

09th and 10th May 2025, gapHQ, Colombo 07, Sri Lanka

MESSAGE FROM THE CONFERENCE CO-CHAIRS

It is with great pleasure that we extend a warm welcome to all participants of the Colombo Conference – the Second International Conference on University-Industry Collaborations for Sustainable Development (ICSD 2025) in the vibrant city of Colombo, Sri Lanka. The chosen theme, "University Industry Collaborations for Sustainable Development," resonates deeply with the global imperative for fostering innovative and sustainable research to shape a brighter future. In organizing this conference, our vision is to create a dynamic convergence point for talents, knowledge, and dedication. We believe that this platform will serve as a crucible for the generation of groundbreaking ideas and the exchange of expertise among participants dedicated to the cause of sustainable global development. Our conference explores diverse sub-topics within the sphere of sustainable development, focusing on the intricate interplay of academia and industry. We anticipate discussions spanning a wide range of subjects, each contributing to the overarching goal of advancing sustainable research practices for the benefit of future generations. The selected, leading full papers of the Colombo Conference (ICSD 2025) will be published by Springer Nature under the book series Proceedings in Technology Transfer. All other accepted papers will be published in a special volume of proceedings with an international standard book number (ISSN). The choice of Colombo as our host city holds significance, as it is a city steeped in rich heritage, unique architecture, cultural diversity, and natural beauty. We hope that amidst the intellectually stimulating sessions, you find moments to relish the distinctive charm and climate of Colombo. Our heartfelt gratitude goes out to our distinguished guests, keynote speakers, authors, members of the international advisory committee, and the dedicated editorial committee. We extend sincere appreciation to our sponsors and all those who have generously volunteered their time and efforts to ensure the success of this pivotal event. As conference co-chairs, we are honored to be part of this collaborative journey towards sustainable development. We look forward to witnessing the flourishing exchange of ideas and forging lasting connections during this memorable event.

Prof. Ranjith Dissanayake
Prof. G. Yugantha Jayasinghe
Prof. Sujeeva Setunga
Prof. Dilanthi Amaratunga
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The Second International Conference on University-Industry Collaborations for Sustainable Development (ICSD 2025) 09th and 10th May 2025, gapHQ, Colombo 07, Sri Lanka

TABLE OF CONTENTS

PREFACE	iii
MESSAGE FROM THE CONFERENCE CO-CHAIRS	iv
AGROINDUSTRY’S TRENDS, PATTERNS, AND DEVELOPMENTAL IMPACTS	
ADVANCEMENTS IN CLIMATE-RESILIENT CROPS: TRENDS, CHALLENGES, AND THE PATH FORWARD FOR SUSTAINABLE AGRICULTURE	1
BARRIERS AND ENABLERS OF DIGITAL PLATFORM ADOPTION FOR ECONOMIC EMPOWERMENT IN RURAL SRI LANKA: A CONCEPTUAL FRAMEWORK	11
CIRCULAR ECONOMY FOR SUSTAINABLE DEVELOPMENT	
INVESTIGATION OF THE CARBON EMISSION REDUCTION TARGETS TOWARDS SUSTAINABILITY -A FOCUS ON 3PL COMPANIES IN SRI LANKA.....	21
ADVANCING CIRCULARITY IN THE CONSTRUCTION SECTOR: A SYSTEMATIC REVIEW OF INNOVATIVE PRACTICES, DIGITAL TECHNOLOGIES, AND POLICY FRAMEWORKS FOR SUSTAINABLE RESOURCE MANAGEMENT.....	31
POTENTIAL, CHALLENGES, AND STRATEGIC IMPLEMENTATION OF FLOATING SOLAR PHOTOVOLTAIC (FPV) TECHNOLOGY IN SRI LANKA	43
CIRCULAR ECONOMY FOR RESILIENT DISASTER RECOVERY: STRATEGIES FOR SUSTAINABLE REBUILDING AND COMMUNITY EMPOWERMENT.....	65
CLIMATE-SMART AGRICULTURE FOR A RESILIENT AND FOOD-SECURE FUTURE	
ASSESSMENT OF TIMBER AUTHENTICITY IN SRI LANKA: A CASE STUDY ANALYSIS	75
STAKEHOLDERS IN FLOOD RISK MANAGEMENT: A CASE STUDY OF THE NILWALA RIVER IN SRI LANKA.....	81
GROWTH AND YIELD RESPONSE OF TURMERIC (<i>Curcuma longa</i> L.) TO VARYING TEMPERATURE AND RELATIVE HUMIDITY UNDER OPEN FIELD AND GREENHOUSE CONDITIONS	95
ENHANCING THE DURABILITY OF FINGER- JOINTED PINE (<i>Pinus caribaea</i>) WOOD TO MITIGATE CLIMATE CHANGE.....	104
ADOPTION OF SOILLESS CULTIVATION IN URBAN SRI LANKA: PUBLIC PERCEPTION, BARRIERS, AND OPPORTUNITIES.....	112
IMPACT OF NATURAL AGING ON THE PHYSICOCHEMICAL PROPERTIES OF WHEAT FLOUR DURING SHORT-TERM STORAGE: IMPLICATIONS FOR BAKING QUALITY AND SHELF-LIFE OPTIMIZATION	122
EMERGING TECHNOLOGIES FOR RESILIENT AGROECOSYSTEMS	
SWOT ANALYSIS ON CIRCULAR ECONOMY PRACTICES IN FISHERIES SECTOR IN SRI LANKA; A CASE STUDY IN SOUTHERN COASTAL BELT OF SRI LANKA.	131

ENVIRONMENTAL ENGINEERING INNOVATIONS FOR SUSTAINABLE RESOURCE MANAGEMENT.....

COMPARISON OF ANAEROBIC CO-DIGESTION OF CHEESE WHEY WITH GARDEN WASTE AND KITCHEN WASTE 143

MULTI-CRITERIA DECISION MAKING APPROACH FOR SELECTING THE OPTIMAL METHOD FOR ANTIBIOTIC REMOVAL FROM WASTEWATER..... 152

SOLUTION FOR URBAN SUSTAINABILITY: A COLLABORATIVE APPROACH FOR DISASTER MANAGEMENT AND COMMUNITY AWARENESS 168

INNOVATIVE APPROACHES TO SUSTAINABLE FOOD PRODUCT DEVELOPMENT

DETERMINATION OF THE KNOWLEDGE, ATTITUDES, AND UTILIZATION OF COOKING OIL AMONG FAMILIES OF APPLIED SCIENCES UNDERGRADUATE STUDENTS IN A SELECTED UNIVERSITY, SRI LANKA..... 180

DEVELOPMENT OF READY TO SERVE (RTS) FLAVOURED COFFEE BEVERAGES USING ROBUSTA COFFEE..... 192

ENHANCING CONSUMER PREFERENCE OF ROBUSTA INSTANT COFFEE BY INCORPORATING MICROENCAPSULATED CINNAMON; DEVELOPMENT AND PHYSICOCHEMICAL ASSESSMENT OF A FLAVORED INSTANT COFFEE 208

INNOVATIVE TECHNOLOGICAL AND MATERIAL ADVANCEMENTS FOR SUSTAINABLE INDUSTRIAL AND HEALTHCARE APPLICATIONS

INVESTIGATION OF SELF-HEALING CONCRETE USING COCONUT WAX EPOXY CAPSULES 221

INVENTION AND INNOVATION

MACHINE LEARNING FOR EARLY DETECTION OF MOTOR DYSFUNCTION IN PARKINSON'S DISEASE USING 6-AXIS IMU DATA 230

IDENTIFYING OPTIMAL VEGETATION INDICES AND REMOTE SENSING METHODS FOR ACCURATE YIELD PREDICTION IN SRI LANKAN TEA PLANTATIONS: A SYSTEMATIC REVIEW..... 239

MICROPLASTICS AND PLASTICS: CHALLENGES, INNOVATIONS, AND SUSTAINABLE SOLUTIONS

UNDERGRADUATES' AWARENESS AND PERCEPTIONS ON MICROPLASTICS: A CASE STUDY ON SABARAGAMUWA UNIVERSITY OF SRI LANKA..... 250

EXTRACTION OF CHITOSAN FROM SHRIMP EXOSKELETON AND DEVELOPMENT OF ECO-FRIENDLY BIOPLASTICS: A SUSTAINABLE WASTE TO-RESOURCE APPROACH. 259

UNIVERSITY-INDUSTRY PARTNERSHIPS FOR SUSTAINABLE DEVELOPMENT

ASSESSING TECHNICAL EFFICIENCY OF PUBLIC SCHOOLS IN SRI JAYAWARDENAPURA EDUCATION ZONE THROUGH DATA ENVELOPMENT ANALYSIS 271

ROLE OF UNIVERSITY INDUSTRY COLLABORATION IN UPGRADING THE SMALL-SCALE DRY FISH VALUE CHAIN OF SOUTH SRI LANKA 283

INNOVATIVE ECO-FRIENDLY SUPERHYDROPHOBIC COATING FOR POLYESTER
UMBRELLA FABRICS: ENSURING LONGEVITY AND WATER RESISTANCE 298

AGROINDUSTRY'S TRENDS, PATTERNS, AND DEVELOPMENTAL IMPACTS

**ADVANCEMENTS IN CLIMATE-RESILIENT CROPS: TRENDS, CHALLENGES,
AND THE PATH FORWARD FOR SUSTAINABLE AGRICULTURE****R. M. Y. I. Rathnayake, W. G. I. Madushani, D.L.C.K. Fonseka****Department of Crop Science, Faculty of Agriculture, University of Ruhuna, Matara, Sri Lanka.***Correspondence E-mail :dlckumari@crop.ruh.ac.lk, TP: +94767327109*

Abstract: Climate change poses a critical threat to global food security by intensifying environmental stressors such as extreme temperatures, erratic rainfall patterns, and increasing pest and disease challenges that conventional crops often fail to withstand. This study aimed to explore recent advancements and current trends in developing and adopting climate-resilient crops, with the broader goal of supporting sustainable agriculture under changing climatic conditions. A comprehensive literature review was conducted using databases such as Google Scholar, Scopus, and Web of Science, focusing on peer-reviewed publications from 2005 to 2024. Key search terms included "climate-resilient crops," "abiotic stress tolerance," and "modern and conventional breeding techniques." The findings reveal that combining traditional breeding, molecular tools like marker-assisted selection and genetic selection, and cutting-edge biotechnologies such as CRISPR/Cas9 gene editing has significantly enhanced crop tolerance to drought, heat, salinity, and pest infestations. The integration of artificial intelligence and microRNA research further supports high throughput phenotyping and stress response optimization. In conclusion, while technological innovations have accelerated the development of climate-resilient crops, their widespread adoption requires robust policy frameworks, increased investment in education and breeding infrastructure, and inclusive strategies that consider socio economic contexts. Advancing climate-resilient agriculture is essential to mitigate the impact of climate change and ensure global food security for future generations.

Keywords: Adaption; Climate Change; Climate Resilient; Genetic Diversit

1.Introduction

Global climate change refers to a change in the long-term weather patterns that define various parts of the world. 'Weather refers to the short-term (daily) variations in temperature, wind, and/or precipitation in a specific area'(Mahato, 2014). Agriculture is an important factor to consider when it comes to climate change (S.Spaldon, 2015). Because agricultural produces mostly influence by the climate factors such as temperature, precipitation, soil moisture, and sea level (Cockel et al., 2022). Climate change is caused as a result of releasing GHGs to the atmosphere. GHGs releasing to the atmosphere by human activities, burning of vegetation, fossil fuel combustion and industrialization (Cresser et al., 2008). Increased levels of GHGs, carbon dioxide (CO₂), water vapor (H₂O), methane (CH₄), nitrous oxide (N₂O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF₆) trap heat in the atmosphere which have contributed to an overall rise in the earth's temperature, resulting in global climate changes (Mahato, 2014). Methane has the biggest global warming potential, approximately 300 times that of CO₂ and 20 times that of N₂O. The agriculture industry is both a contributor and a victim of climate change, due to nitrogen fertilizers, flooded rice fields, soil management, land conversion, biomass burning, livestock production, and associated manure management(Saboor et al., 2011).

The consequences of climate change will cause changes such as rising sea levels, shifting rainfall patterns, and shifting climatic areas. Climate change leads to intensify droughts, storms, and floods. According to the IPCC (2007), global temperature will rise by 1.8°C to 4°C, with an average increase of 2.8°C. Human activities, have led to a rise in CO₂ concentration from 280 ppm to 380 ppm (Saboor et al., 2011).This will rise to 605-755 ppm by 2070 (Kalra et al., 2007). Given these challenges, producing climate-resilient crops has become an essential, these are made to resist the negative consequences of adverse weather conditions, ensuring stable yields and promoting food security. Innovative breeding approaches that combine conventional and modern technologies to increase crop resilience are needed to achieve this aim (Koshariya, 2022a).

To address future agricultural issues from both local and global perspectives in order to produce climate resilient crops. Recognizing how multifactorial stress affects semi domesticated plants, wild relatives, and cultivated plants is essential. Global plant production has to diversify by introducing new crops or producing better cultivars of staple crops in order to increase food security (Kopeć, 2024). It is now essential to make the best use of the remaining arable land and water while maximizing output to meet the growing demand for food. Developing climate resilient crops is crucial because they will perform better than conventional crops under any combination of abiotic stressors (heat, drought, and salt) (Sugumar et al., 2024a). Therefore, improving crops that support the growth of climate resilient agricultural projects is essential today. Reduced agricultural yields are a direct result of the extreme weather events that follow climate change. Climate resilient cultivars and crops allow farmers to adapt to climate change. These crops avoid crop failure and productivity reduction by producing consistently in new environmental circumstances (Koshariya, 2022a).

The most current advancements and trends in crop production for climate resilience are examined in this review, covering both conventional and modern methods. Crops that can withstand extreme weather events including heat waves, droughts, floods, and cold spells must be developed since these occurrences are becoming more often and severe (Peric et al., 2024,Kole et al., 2015)

2.Methodology

This review systematically synthesizes recent advancements in climate resilient agricultural production, with a specific focus on breeding strategies and adaptive crop traits. The methodology comprises three primary components: comprehensive literature retrieval, rigorous selection and extraction protocols, and conceptual framing grounded in multi-scalar resilience.

2.1 Literature Search and Selection

Relative academic publications, research papers, conference proceedings, and reports were obtained by searching appropriate databases such as Google Scholar, Scopus, Web of Science, and PubMed. Search terms included "modern and conventional breeding techniques," "abiotic stress tolerance in crops," "crop breeding for climate change," "climate-resilient crops," and "sustainable agriculture." Studies published within the last 20 years (2005–2024) were given priority in order to guarantee the inclusion of recent developments. Peer-reviewed journal publications, books, and reports from governmental or non-governmental organizations (NGOs) on climate-resilient crop production were included in this review.

Additionally, studies examining the effects of climate change on crop productivity and research on conventional and modern breeding techniques were also included. This review excluded non-peer-reviewed publications and opinion articles that lacked empirical data, studies unrelated to agricultural or crop resilience, and research focusing exclusively on animal adaption techniques.

2.2 Data Extraction and Synthesis

The selected literature was systematically reviewed, with key information extracted on climate-resilient breeding techniques (e.g., selective breeding, genetic modification, gene editing), crop traits associated with climate resilience (e.g., drought tolerance, heat resistance, salinity tolerance), and challenges and opportunities for climate-resilient crop adoption (e.g., farmer awareness, seed costs, regulatory policies). The gathered data was then synthesized to detect new trends, technical developments, and gaps in existing studies.

2.3 Conceptual Framework: Climate Resilience as a Multi-Trait, Multi-Scale Phenomenon

This review adopts a conceptual framework that situates climate resilience as a complex, dynamic attribute expressed across multiple biological and agronomic levels:

Climate resilience in crops can be considered a dynamic trait complex that manifests at three scales,

On Physiological Level: Characters such as osmotic adjustment, stomatal regulation, antioxidant activity, etc (Sarkar et al., 2019).

Molecular Level: Expression of genes responsive to stress, regulatory microRNAs and epigenetic changes (Sugumar et al., 2024b).

Agronomical Level: Stability of yield in varying environments, adaptability to marginal soils and reduced input requirements (Kopeć, 2024).

2.4 Discussion and Future Directions

Based on the findings, this review investigates the feasibility of scaling up climate-resilient crops, evaluates existing policy frameworks, and identifies key areas for future research, concluding with recommendations to enhance the adoption of these crops as a strategy to address climate change challenges. This methodological framework provides a systematic and rigorous approach to analyzing recent trends in climate-resilient crop production while ensuring academic integrity and relevance.

3. Results and Discussion

3.1 Climate Change and Its Impact on Agriculture

The most significant ways that climate change impacts agricultural production is through increased environmental stressors, unpredictable weather patterns, and rising temperatures, which can cause heat stress in crops, which lowers photosynthesis and ultimately yields and changes in precipitation patterns, such as extended droughts or heavy rainfall, which further interfere with planting and harvesting schedules and make crop management more difficult.

While climate change produces both beneficial and detrimental outcomes for agricultural productivity, the effects will display regional differences worldwide. The agricultural dependency of populations in developing nations makes them particularly vulnerable to climate change because they lack both the technical expertise and the financial resources to manage increasing variability (Karki & Gurung, 2012). The impact of climate change on agriculture remains complex because its effects will differ across different global regions. Global agricultural practices will experience shifts due to changes in temperature levels, rain patterns, and carbon dioxide concentrations, which will particularly affect tropical regions (Prasanna et al., 2013).

Agricultural production could suffer negative outcomes from climate change through geographic changes in farming areas and crop yields alongside decreased water resources for irrigation and land erosion due to rising sea levels and increased salinity. Modifications in soil moisture levels, atmospheric temperature, rainfall patterns, cloud coverage and CO₂ concentrations can affect crop production quantities and regional boundaries (Prasanna et al., 2013).

Soil properties may experience changes that result in the loss of soil organic matter and nutrient leaching as well as salinization and erosion. The possibility of agricultural losses from weeds, insects, and diseases will probably rise. The effects of climate change drive the excessive use of pesticides and biodiversity loss which leads to plant pest and disease outbreaks. As sea levels rise, agriculture in low-lying coastal areas and river deltas faces challenges from flooding which threatens regions prone to flooding such as China and Eastern Asia. According to Cresser et al., 2008 rising temperatures and rainfall patterns pose serious threats to agricultural sustainability due to increased costs and damage.

Although climate change creates major obstacles, it could also have certain advantages. While more rain in some areas might enhance irrigation and general production capacity, higher temperatures could lengthen the growing season in certain high latitude areas. These advantages, meanwhile, are very dependent on soil conditions and regional climate variables (Cresser et al., 2008).

Higher temperatures may result in changes in animal husbandry methods, lower milk production, lower feed conversion rates, and hinder reproductive efficiency and weight gain due to climate changes. The spread of livestock related pests, including ticks and flies, might also rise under warmer conditions. According to Cresser et al., 2008, intensively managed livestock systems are expected to have more adaptive capacity than mixed livestock cropping systems (Chapman et al., 2012).

Dealing with these issues calls for the development and production of climate resilient crops able to endure environmental stresses while preserving consistent yields. Agricultural systems can be more flexible to fit changing climate by combining traditional breeding techniques with current biotechnological developments, therefore guaranteeing food security for future generations.

3.2 Importance of Climate-Resilient Crops

Crops that are designed to endure the negative consequences of shifting weather patterns, including higher temperatures, modified precipitation, and greater pest and disease pressures, are known as Climate resilient crops (Figure 2). In the face of environmental uncertainty, these crops are absolutely essential to guarantee a consistent food supply (“Plant Breeding for Climate Resilience: Strategies and Genetic Adaptations,” 2024).

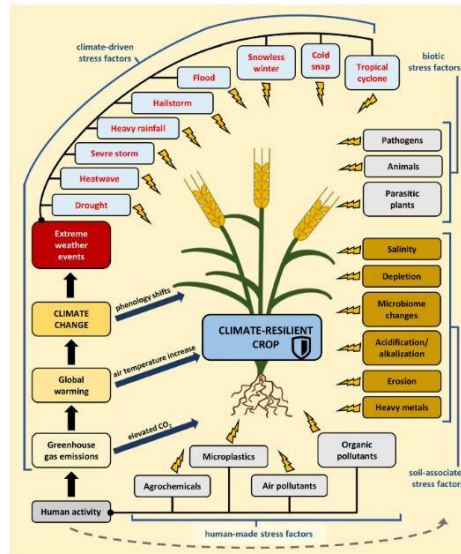


Figure 1: The climate resilient crop (Kopec, 2024)

To ensure the food security of billions of people around the world who depend on agriculture for their livelihoods, improving agricultural production and profitability while reducing risks is especially important. Maintaining and raising agricultural yields in the face of climate change problems depends on developing and adopting climate resilient crop varieties with enhanced tolerance to heat, drought, floods, cold, and salinity stress (Sarkar et al., 2019).

3.3 Tolerance to Abiotic Stresses in Climate-Resilient Crops

Abiotic stress tolerance is what allows plants to endure and reproduce under difficult environmental conditions, including limited resources, high temperatures, or drought. It also includes a plant's ability to bounce back fast and keep great production potential once the stress is lifted. The genetic relationship between stress tolerance and resource use efficiency controls genetically in some crops is critical for creating climate resilient types that can raise crop output since it is quantitatively inherited. While guaranteeing tolerance to several abiotic stresses including heat, drought, floods, and salinity, crop improvement initiatives seek to increase production. Farmers need varieties of crops that provide acceptable yields under stress circumstances but preserve great production potential under good conditions (Sarkar et al., 2019)

Drought Tolerance

Among the main qualities of climate resilient plants is their capacity to withstand drought. These plants can endure times of water shortage by means of strong root systems and effective water-use mechanisms. Climate-resilient plants grow and produce even under extended droughts, therefore promising a consistent food supply and supporting food security in areas vulnerable to water shortages (Zafar et al., 2023).

Key drought tolerance mechanisms include:

- **RSA (Root System Architecture):** Deep and densely branched roots facilitate efficient water uptake from lower soil profiles (Zafar et al., 2023).
- **Stomatal Regulation:** Partial or complete closure of stomata reduces transpirational water loss, conserving internal moisture during stress (Sarkar et al., 2019).
- **Accumulation of Osmolytes:** Compatible solutes such as **proline** and **glycine betaine** stabilize cellular structures and maintain turgor under dehydration stress (Sugumar et al., 2024b).
- **Activation of Drought-Responsive Genes:** Gene families such as **DREB**, **NAC**, and **LEA**

play essential roles in regulating osmoprotection, water retention, and stress signaling pathways (Haroon et al., 2022).

Heat Resistance

Agricultural output is greatly threatened by extreme temperatures, especially increasing heat. Engineered to be more resistant to high temperatures, climate resilient crops can preserve photosynthesis and keep yield even under heat stress. Ensuring consistent crop production in areas susceptible to rising temperatures depends on this quality, therefore heat-resistant types will be crucial for future farming (Zafar et al., 2023).

Mechanisms of heat resistance include:

- **Heat Shock Proteins (HSPs):** Function as molecular chaperones that prevent protein denaturation and facilitate proper protein refolding under thermal stress (Kole et al., 2015).
- **Stay-Green Trait:** Delays chlorophyll degradation and leaf senescence, maintaining photosynthetic activity during heat exposure (Zafar et al., 2023).
- **Membrane Thermostability:** Maintains cellular membrane integrity and function under high-temperature conditions, supporting physiological resilience (Razzaq et al., 2022).

Adaptability

Adaptability is another essential characteristic of climate resilient crops, which enables them to flourish in a variety of soil types and climatic conditions.

Because of their adaptability these crops are essential to sustainable agriculture, which guarantees consistent crop production in a range of environmental conditions. Climate resilient crops contribute to global food security by reducing the risks associated with climate variability and sustaining productivity across varied regions and under changing conditions (“Plant Breeding for Climate Resilience: Strategies and Genetic Adaptations,” 2024)

Examples of adaptive traits include:

- **Na⁺ / K⁺ Homeostasis:** Genes such as **SOS1** and **HKT** regulate ionic balance under saline conditions, preventing toxic ion accumulation and maintaining metabolic function (Sugumar et al., 2024b).
- **Aerenchyma Formation:** Development of intercellular air spaces in root tissues enables oxygen transport during waterlogging, enhancing survival under submerged or poorly drained soils (Koshariya, 2022a).
- **Pest and Disease Resistance**
The need for chemical pesticides is decreased by climate-resilient crops' natural resistance to common pests and diseases. Because it reduces environmental impact and ensures consistent harvests despite pest and disease pressures, this inherent resistance encourages more sustainable farming practices. These crops lower the costs of agricultural inputs, promote food security, and protect the environment by lessening the detrimental effects of pests and diseases (Razzaq et al., 2022).

These defense strategies include:

- **Constitutive Defense Mechanisms** such as **thickened cuticles**, **dense trichomes**, and the production of **secondary metabolites**, which serve as physical and chemical barriers to pest and pathogen invasion (Razzaq et al., 2022).
- **Inducible Responses** including the **activation of pathogenesis-related (PR) proteins** and the initiation of **systemic acquired resistance (SAR)** upon infection or stress exposure (Sarwar et al., 2002).

3.4 Trends in Climate-Resilient Crop Varieties

Complex factors, such as institutional, cultural, economic, and biophysical considerations, are involved in climate change adaptation (Bryant et al., 2000). Reducing harm, preventing damage, or taking advantage of new opportunities are the objectives of adaptation to present or predicted climate impacts (Field et al., 2014). For natural systems to adapt to climate change and its effects, human intervention

is essential (Akinragbe & Irohibe, 2015). The vulnerability of systems, which is influenced by exposure, sensitivity, and adaptive capacity, is frequently associated with adaptation efforts. Long term adaptation depends on social-ecological systems' resilience, or their capacity to reorganize and change in a sustainable way (Bryant et al., 2000).

As the focus of climate change research and policy has shifted from mitigation to adaptation, Strategies that assist resource poor farmers in becoming more resilient to the effects of climate change have become increasingly important (Shaw et al., 2013). New agricultural management techniques have been made available to help farmers deal with erratic climate patterns, such as crop diversification, drought resistant cultivars, small livestock farming, beekeeping, and small scale irrigation (Perez et al., 2010). The continued use of unsustainable and rigid farming systems has resulted in food insecurity and the loss of livelihoods, despite their contributions to food security (Yila & Resurreccion, 2013).

Integration of Modern Biotechnology and Traditional Breeding

To create climate-resilient crops, modern biotechnology combined with traditional breeding techniques is used. Traditional breeding methods concentrate on choosing and crossing cultivars that possess desired characteristics, including resistance to pests or drought. Although it might take years, this approach has produced several crop types that are climate resist (Kole et al., 2015). Climate resilient crop development has increased recently thanks to modern biotechnological technologies including genetic engineering and marker-assisted selection (Zafar et al., 2022).

Marker Assisted Selection and Genetic Selection

Genetic selection (GS) and marker assisted selection (MAS), two developments in molecular breeding techniques, speed up the breeding process by allowing for accurate trait selection at the DNA level. Because they enable precise alterations of individual genes linked to stress tolerance. With the use of marker assisted selection, plant breeders may precisely choose and create crop types that are adaptable to climate change (Robyn Anderson et al., 2020). Through the use of certain genetic markers linked to desired qualities, such as disease resistance or drought tolerance, MAS aims to speed up the breeding process. Genetic selection is a genetic technique that uses computer algorithms to analyze a plant's genome to predict its performance and select desired features, such as climate resistance. This method has revolutionized plant breeding by enabling better decision making over plant selection. Its ability to manage pests, heat, and drought resistance allows for the creation of crop varieties suitable for changing climates (Sarwar et al., 2002)

CRISPR/Cas9 and Gene Editing

Gene editing technologies, in particular, CRISPR/Cas9 have completely changed crop improvement. Using CRISPR/Cas9 to effectively modify certain genes. Through the targeting of genes implicated in stress response pathways, this method has been utilized to create crops with enhanced resistance to heat, drought, and flooding (Koshariya, 2022a).

Genetic Engineering for Climate Challenges

In addressing climate challenges such as drought and disease resistance, Genetic engineering is instrumental. In water scarce conditions, Drought-resistant crop varieties can continue to grow and produce yields while pest resistant crops can reduce the need for chemical pesticides. Bt cotton, a famous example of genetic engineering for climate resilience, has significantly reduced the need for chemical insecticides and improved cotton yields (Haroon et al., 2022). These genetic methods will be essential to maintaining food security and sustainability as climate change continues to affect agriculture worldwide

Role of Artificial Intelligence in Crop Improvement

As climate change continues to impact agriculture globally, these genetic techniques will be crucial to preserving food security and sustainability. Artificial intelligence (AI) has introduced genetic algorithm-based hybrid models to predict the stress tolerance index in plants, assessing genotypes based on crop production, management strategies, and climatic conditions. Deep learning algorithms can recognize genes differentially expressed under controlled and stressed conditions. Multispectral sensors and imaging technologies contribute to non-destructive modeling, allowing for non-destructive phenotyping of beneficial traits. Recent advancements include biosensing miRNA concentrations and digitizing stress response, reducing laboratory work in abiotic stress research (Sugumar et al., 2024b).

Role of MicroRNAs in Stress Tolerance

Application of miRNAs, since they control the expression of important genes involved in stress response networks, microRNAs (miRNAs) may act as mediators of stress tolerance in plants. Their length ranges from 21 to 23 nt, and they use either mRNA decay or post-transcriptional regulation to suppress the production of the target mRNA. Several miRNAs have been discovered recently by high throughput sequencing techniques, which has aided studies on their function in abiotic stress tolerance (Sugumar et al., 2024b).

Genotyping and Phenotyping for Resilience

Combining Genotyping with Phenotyping, using both genotyping and phenotyping techniques, is essential for breeding crops that can withstand climate change. High throughput phenotyping tools (drones and remote sensing) offer comprehensive information on how crops behave under different stressors, which may be used to find genetic markers associated with resilience features (Koshariya, 2022b).

Together, these trends in genetic techniques, biotechnological innovations, and AI driven approaches are advancing the creation of climate-resilient crops capable of ensuring food security in a changing climate.

4. Conclusion

Climatic resilient agriculture has enormous potential to address the problems caused by climate change, but achieving it presents significant obstacles. Technological developments in plant breeding contribute to new trends that can withstand extreme weather conditions. However, these technologies must be combined with an extensive knowledge of socioeconomic and ethical factors to ensure that climate resilience is achieved sustainably and equitably.

Farmers and ecosystems need protection, and innovative, adequate policies and regulations are essential for fostering climate-resilient agriculture. Concerted efforts from research organizations and extension policymakers were necessitates to promote climate resilient crops and their development. Therefore, establishing regulatory policies for gene-edited crops, investing in advanced breeding techniques, and enhancing education for workers in the field should be promoted.

In summary, legislation that supports the preservation of genetic diversity and the availability of climate resistant cultivars will promote the development of sustainable agriculture, which is crucial in the context of ongoing climate change.

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BARRIERS AND ENABLERS OF DIGITAL PLATFORM ADOPTION FOR ECONOMIC EMPOWERMENT IN RURAL SRI LANKA: A CONCEPTUAL FRAMEWORK

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Abstract: Digital platforms are increasingly recognized as tools for economic empowerment in rural Sri Lanka, providing access to employment, skill development, and financial inclusion. This study investigates the enablers and barriers to digital platform adoption in six rural provinces through a mixed-methods approach, combining survey responses from 107 participants with thematic analysis of open-ended questions. Quantitative findings reveal high levels of device ownership, with 90.7% of respondents owning smartphones, 86.0% owning laptops, and 81.3% having internet connectivity. However, 28.0% of respondents still reported difficulties in accessing digital platforms. Key barriers included unreliable or costly internet (26%), lack of affordable devices (21%), insufficient digital literacy (16%), cybersecurity risks (18%), and platform complexity (19%). Cross-tabulation and correlation analyses demonstrate a strong positive association between income and digital access ($r = 0.59$ with internet access), and a significant correlation between education and advanced platform usage (freelance/remote work, $r = 0.99$). Thematic analysis highlights user demand for subsidized devices (22%), expanded internet access (33%), and localized digital literacy training (22%). A conceptual framework developed from the findings illustrates the interplay of access enablers (infrastructure, affordability), capability enablers (training, literacy), and barriers (security, complexity) in determining digital economic outcomes. Addressing these barriers through coordinated policy and community interventions is essential for bridging the rural digital divide and realizing inclusive economic growth.

Keywords: Adoption; Barriers and Enabler; Conceptual Framework; Digital Inclusion; Digital Platform; Economic Empowerment; Rural Sri Lanka

1.Introduction

In recent years, digital platforms have emerged as powerful enablers of economic growth and social inclusion across the globe. Technologies such as ride-sharing apps, e-commerce platforms, and freelance marketplaces have transformed how individuals access markets, employment, and income-generating opportunities (UNCTAD, 2019). Particularly in developing economies, these platforms are increasingly seen as tools for bridging gaps in infrastructure, enabling financial inclusion, and reducing unemployment among marginalized populations (World Bank, 2021). The growing phenomenon of "Uberization" the decentralization and digitization of service delivery — has played a pivotal role in facilitating micro-entrepreneurship, especially in underserved regions (Sundararajan, 2016).

In Sri Lanka, the government and private sector have recognized the potential of digital technologies to stimulate rural development and economic empowerment. Initiatives such as the Digital Economy Strategy, e-governance projects, and mobile-based financial services have sought to enhance connectivity, promote digital literacy, and expand digital infrastructure in remote areas (ICTA, 2020;). Despite these efforts, significant disparities remain between urban and rural communities in terms of digital access and usage. Many rural residents continue to face challenges such as limited internet connectivity, lack of affordable devices, low levels of digital literacy, and concerns about data privacy and cybersecurity (Department of Census and Statistics, 2021; Fernando et al., 2022; Seneviratne,2023).

While global studies have examined the digital divide and its socioeconomic implications, there is a paucity of empirical research focused on the specific barriers rural Sri Lankans encounter when attempting to engage with digital platforms for economic purposes. Understanding these constraints is critical, particularly as digital inclusion is increasingly tied to economic empowerment, social mobility, and resilience in the face of crises such as the COVID-19 pandemic (GSMA, 2021).

Therefore, the objective of this study is to investigate the barriers and challenges that rural populations in Sri Lanka face in accessing and using digital platforms for economic purposes. By identifying and analyzing these constraints, the study aims to inform inclusive digital policy interventions and support efforts to bridge the rural-urban digital divide in Sri Lanka.

2.Literature review

2.1 Theoretical Background

The study of digital access barriers is grounded in several interrelated theoretical frameworks, including the Digital Divide theory, the Technology Acceptance Model (TAM), and Digital Inclusion frameworks. The Digital Divide theory refers to the gap between individuals, households, and geographic areas at different socio-economic levels in terms of access to, use of, or knowledge of information and communication technologies (ICTs) (van Dijk, 2006). The divide is not merely about physical access to the internet or devices, but also encompasses disparities in skills, usage patterns, and the outcomes derived from technology use. Scholars have distinguished between the first-level digital divide (access to devices and connectivity), second-level divide (skills and usage), and the third-level divide (outcomes and benefits) (Wei et al., 2011).

The Technology Acceptance Model (TAM), developed by Davis (1989), posits that two main factors—Perceived Ease of Use (PEU) and Perceived Usefulness (PU)—influence an individual's intention to adopt and use a technology. In rural and low-resource settings, perceptions of complexity, trustworthiness, and utility of digital tools can significantly affect the uptake of digital platforms (Venkatesh & Bala, 2008). For instance, if users perceive digital services to be too complex or irrelevant to their livelihood activities, their willingness to engage with such platforms diminishes.

Digital Inclusion frameworks, meanwhile, emphasize equitable access to technology and digital skills as fundamental to socio-economic empowerment (Helsper, 2012). These frameworks highlight a holistic approach that combines infrastructure development, affordable devices, digital literacy, relevant content, and socio-cultural acceptance to ensure meaningful participation in the digital economy. Digital inclusion is now widely recognized as essential for promoting inclusive growth and achieving Sustainable Development Goals (UNESCO, 2021).

2.2 Empirical Studies in Rural and South Asian Contexts

Empirical studies across South Asia reveal persistent challenges in bridging the digital divide, particularly in rural areas. In India, for example, Mehta and Chatterjee (2020) found that lack of digital literacy, poor infrastructure, and gender-based constraints limit rural populations from benefiting fully from digital government services and online commerce. Similarly, in Bangladesh, Kabir et al. (2019) observed that despite increasing smartphone penetration, rural micro-entrepreneurs struggled with app usage due to low education levels and lack of localized content.

In Sri Lanka, studies by Fernando, Jayasundara, and Perera (2022) emphasize the mismatch between infrastructure availability and actual use of digital platforms. While mobile network coverage has expanded, poor signal quality and high data costs continue to hinder rural usage. Another study by Samarajiva and Zainudeen (2018) noted that although digital finance tools (like mobile money) were available in rural Sri Lanka, adoption remained low due to lack of trust, low awareness, and fear of fraud. These studies collectively suggest that technological availability does not automatically translate into meaningful use. Instead, a complex interplay of economic, educational, infrastructural, and social factors determines whether digital tools contribute to rural empowerment.

2.3 Key Constructs in Digital Platform Adoption

The literature identifies several constructs critical to understanding digital platform adoption in rural settings. Digital literacy (Ng, 2012) encompasses both basic and advanced competencies needed to navigate digital environments. Access to digital infrastructure including internet connectivity and affordable devices is fundamental to engagement and use (ITU, 2020). Drawing from the Technology Acceptance Model, perceived ease of use and perceived usefulness are shown to influence individuals' adoption behavior. Social influence, particularly significant in collectivist societies like Sri Lanka, also shapes digital behavior (Venkatesh et al., 2003). Moreover, perceived risk related to privacy, security, and trust in platforms—emerges as a barrier to adoption. Finally, economic empowerment is considered a key outcome, reflecting users' enhanced income, opportunities, and autonomy resulting from platform use. Together, these constructs provide a conceptual basis for analyzing digital engagement and its socioeconomic impact in rural Sri Lanka.

3. Methodology

This study adopted a mixed-method research design to investigate the barriers and enablers of digital platform adoption in rural Sri Lanka. By integrating both quantitative and qualitative approaches, the research aimed to provide a comprehensive understanding of access challenges, usage patterns, and contextual influences. The quantitative component involved structured questionnaires designed to assess key variables such as digital literacy, access to infrastructure, and perceived ease of use. Complementing this, the qualitative component comprised open-ended questions that elicited detailed insights into user experiences and perceptions, allowing for deeper exploration of themes that emerged from the survey data. This methodological triangulation enhanced the validity and depth of the findings (Creswell & Plano Clark, 2018). A purposive sampling strategy was employed to select participants from six rural provinces—North Central, Eastern, Southern, Uva, North Western, and Sabaragamuwa—ensuring geographic diversity and representation of varied digital experiences. Respondents were drawn from multiple districts within these provinces, including Anuradhapura, Polonnaruwa, Ampara,

Batticaloa, Trincomalee, Hambantota, Matara, Badulla, Monaragala, Kurunegala, Puttalam, Kegalle, and Ratnapura. The sample included individuals engaged in diverse economic activities such as farming, fishing, small business, and self-employment, as well as unemployed individuals, thus capturing a broad socio-economic spectrum. Of the 120 individuals approached, 107 provided valid responses via an online questionnaire. The sample distribution reflected balanced representation across gender, age, education, and income levels, offering a reliable foundation for analyzing factors influencing digital platform usage in rural contexts. Data were collected using a structured questionnaire consisting of both closed- and open-ended questions. The survey instrument was developed based on existing literature on digital inclusion and technology acceptance (Davis, 1989; Helsper, 2012; Venkatesh et al., 2003), and validated through expert review and pilot testing.

The quantitative data collected through structured questionnaires were analyzed using SPSS. Descriptive statistical methods, including frequencies and percentages, were employed to summarize participant responses related to digital literacy levels, access to internet and digital devices, and perceived ease of digital platform usage. This analysis provided a general overview of the digital access environment and user readiness across the surveyed rural populations.

In parallel, the qualitative data derived from open-ended questions were subjected to thematic analysis, following Braun and Clarke's (2006) six-phase methodology. The analysis began with familiarization with the data, followed by generating initial codes, identifying potential themes, reviewing and refining these themes, and finally defining and naming them. The process culminated in the production of a coherent narrative that integrated these themes into the broader research findings. Commonly emerging themes included infrastructure limitations, device affordability, the need for training, and concerns about privacy and cybersecurity. Selected participant quotes were incorporated to exemplify these themes and enrich the interpretation of the quantitative results. The study adhered strictly to established ethical standards. All participants were fully informed of the objectives of the research and their right to voluntary participation. Anonymity was maintained throughout the process, and no personally identifiable information was collected. Informed consent was obtained from all participants, and data confidentiality was preserved. The research was conducted with full respect for the dignity and rights of respondents, ensuring that ethical obligations were fulfilled at every stage of the study.

4. Results and discussion

4.1 Demographic Profile of Respondents

Table 1 summarizes the demographic profile of 107 respondents. The gender split was 60.7% male and 39.3% female. Most participants were aged 18–34, indicating a youthful group. Education levels varied, with 35% completing O/L and 22% A/L, while 17% held diplomas and 11% degrees. Occupations included agriculture (32.7%), self-employment (28%), and informal work (23.4%). Income was evenly spread, with 28% each earning between 10,001–25,000, 25,001–50,000, and over 50,000 LKR monthly.

Table 1: Demographics of the respondent

Variable	Description	Frequency (%)
Gender	Male	65 (60.7%)
	Female	42 (39.3%)
Age	18–24	47 (49.3%)
	25–34	47 (49.3%)
	35–44	8 (7.5%)
	45–54	4 (3.3%)
	55–64	1 (0.9%)
Education	Up to Grade 8	16 (15.0%)
	O/L	37 (35.0%)
	A/L	24 (22.0%)

	Diploma	18 (17.0%)
	Degree	12 (11.0%)
Occupation	Agriculture	35 (32.7%)
	Self-employment	30 (28.0%)
	Informal Work	25 (23.4%)
	Other	17 (15.9%)
Income (LKR/month)	<10,000	17 (15.9%)
	10,001–25,000	30 (28.0%)
	25,001–50,000	30 (28.0%)
	>50,000	30 (28.0%)

4.2 Digital Infrastructure and Platform Usage

Table 2 highlights digital access among respondents. Most owned smartphones (90.7%), laptops (86%), and had internet (81.3%), while basic phone use was lower (39.3%). Perceived ease of access varied; only 9.3% found it very easy, while 28% reported difficulties, indicating ongoing infrastructural challenges in rural areas.

Table 2: Digital Infrastructure

Variable	Description	Frequency (%)
Device Ownership	Smartphone	97 (90.7%)
	Computer/Laptop	92 (86.0%)
	Mobile Phone	42 (39.3%)
	Internet Connection	87 (81.3%)
Ease of Access	Very Easy	10 (9.3%)
	Somewhat Easy	30 (28.0%)
	Neutral	25 (23.4%)
	Difficult	30 (28.0%)
	Very Difficult	12 (11.3%)
Internet Availability	Very Good	8 (7.5%)
	Good	28 (26.2%)
	Moderate	35 (32.7%)
	Poor	26 (24.3%)
	None	10 (9.3%)
Usage Type	Communication	50 (46.7%)
	Online Sales	20 (18.7%)
	Freelance/Remote Work	15 (14.0%)
	Education	12 (11.2%)
	Other	10 (9.3%)

4.3 Platform Engagement Trends

Table 3: Platform Usage

Platform Type	Frequency	Percentage (%)
Ride-sharing (e.g. Uber)	16	15.0%
Delivery (e.g. UberEats)	18	16.8%
Freelancing (e.g. Fiverr)	23	21.5%
E-commerce (e.g. Daraz)	19	17.8%
Facebook Marketplace	28	26.2%
WhatsApp Business	27	25.2%
YouTube	21	19.6%

As shown in Table 3, platform engagement was diverse. Facebook Marketplace (26.2%), WhatsApp Business (25.2%), and YouTube (19.6%) were the most popular platforms. Engagement with formal gig economy apps such as Fiverr (21.5%), Uber (15%), and UberEats (16.8%) was also notable, indicating that rural populations are not merely consumers but also service providers within digital ecosystems.

4.4 Income and Digital Access

Table 4 presents a cross-tabulation between income levels and access to digital devices. Among the lowest income group (<10,000 LKR), 10 respondents lacked all devices, while higher-income groups (>25,000 LKR) had full digital access. Table 5 shows that income is moderately to strongly correlated with smartphone ($r = 0.42$), laptop ($r = 0.53$), and internet ($r = 0.59$) ownership. These results underscore the need for targeted digital inclusion efforts.

Table 4: cross-tabulation between income levels and access to digital devices

Income (LKR)	No Devices	Full Access (All Devices)	Partial Access
<10,000	10	0	7
10,001–25,000	0	27	3
25,001–50,000	0	30	0
>50,000	0	30	0

Table 5: Correlation Matrix of Income and Digital Access

	Income	Smartphone	Laptop	Internet
Income	1.00	0.42	0.53	0.59
Smartphone	0.42	1.00	0.80	0.67
Laptop	0.53	0.80	1.00	0.84
Internet	0.59	0.67	0.84	1.00

4.5 Education Level and Platform Usage

Table 6 shows that respondents with only primary or secondary education primarily used digital tools for communication and online sales, while those with diplomas and degrees were more engaged in freelance and remote work. Table 7 shows that education level is highly correlated with freelance work ($r = 0.99$), while communication ($r = -0.64$) and 'other' platform usage ($r = -0.59$) were inversely related.

Table 6: Education Level and Platform Usage

Education Level	Communication	Education	Freelance/Remote Work	Online Sales	Other
Up to grade 8	9	1	1	3	2
O/L	20	1	2	9	5
A/L	12	4	4	2	2
Diploma	4	4	5	5	0
Degree	3	0	6	2	1

Table 7: Correlation with Education Level

Platform Type	Correlation with Education Level
Communication	-0.64
Education	0.08
Freelance/Remote Work	0.99
Online Sales	-0.32
Other	-0.59

The results highlight that both income and education are critical determinants of digital access and engagement in rural Sri Lanka. Income influences access to infrastructure (devices and connectivity), while education governs the nature of platform usage. These insights are vital for formulating inclusive digital policies that promote equitable access and maximize the economic potential of rural populations through technology.

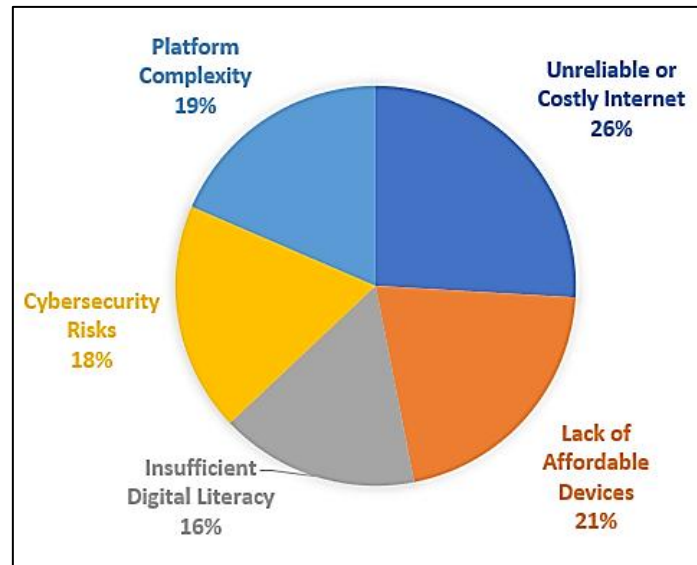


Figure 1: Key Challenges Identified

Figure 1 highlights major barriers to digital platform adoption. The top issue was unreliable or costly internet (26%), followed by lack of affordable devices (21%). Platform complexity (19%) and cybersecurity risks (18%) also posted significant challenges, while insufficient digital literacy (16%) hindered effective usage. These findings reveal that both infrastructural and skill-based limitations affect rural digital engagement, calling for integrated strategies to improve affordability, accessibility, and user competence.

4.6 Thematic Analysis of Open-Ended Responses

Thematic analysis was conducted on five open-ended questions to capture participants' perspectives on digital platform usage, associated challenges, and potential improvements. Responses were coded and analyzed to identify recurring patterns, which were then categorized into key thematic areas.

A common theme among participants was the need for additional support to overcome barriers in digital engagement. Inadequate internet connectivity, unaffordable devices, and limited digital literacy were frequently cited as primary constraints. Many respondents expressed the need for training programs, particularly for those unfamiliar with digital tools. Other challenges included poor customer service, high data costs, and difficulties with time management and platform navigation. Financial constraints and a lack of localized digital support further limited users' ability to benefit from online platforms. In terms of improving digital platforms for poverty eradication, participants suggested several interventions. These included expanding internet access in rural areas, subsidizing devices and data for low-income users, and providing simplified digital literacy training. Additional recommendations emphasized the need for financial literacy and entrepreneurship education via online platforms, along with the reduction of transaction fees and improved user interface design to enhance accessibility and adoption.

Regarding the economic impact of digital platforms, many users reported benefits such as access to freelance and remote work, increased income through online sales and services, and opportunities for skill development. Participants also highlighted time-saving advantages in handling financial transactions and communications. However, some reported only marginal improvements, attributing limited outcomes to infrequent use and a lack of familiarity with available digital resources. Despite positive outcomes, several ongoing challenges hindered the economic utility of digital platforms. Unstable and expensive internet access was a major

barrier, along with cybersecurity concerns such as scams and data privacy issues. High competition, limited digital marketing knowledge, and the complexity of platform interfaces were also cited. Language barriers and limited localized content further restricted meaningful engagement, particularly for less-educated users.

4.7 Conceptual Model: Barriers and Enablers of Digital Economic Empowerment

The conceptual framework developed in this study is informed by both empirical findings from thematic analysis and established theoretical models such as the UNICEF Multiple Overlapping Deprivation Analysis (MODA) framework and the Technology Acceptance Model (TAM) by Davis (1989). It seeks to capture the dynamic interplay between structural access, individual capabilities, and economic outcomes in the context of rural digital platform use.

Findings from the open-ended responses reveal a multidimensional landscape of digital engagement barriers in rural Sri Lanka. Key access barriers include unreliable internet connectivity, limited affordability of devices and data, and geographic isolation. These findings echo global literature that emphasizes infrastructure limitations as critical impediments to digital inclusion in low-income regions (World Bank, 2021; GSMA, 2020). Access-related enablers, such as widespread smartphone ownership and increasing mobile network coverage, however, show promising trends in bridging the rural-urban divide (ICTA, 2020).

The second set of constraints revolves around capability barriers, such as low digital literacy, inadequate training, and the inability to navigate complex platforms. These were strongly expressed by respondents who called for simplified interfaces and localized support. This is supported by Helsper's (2012) digital inclusion framework, which underscores the importance of skills and content relevance for meaningful use. Similarly, Venkatesh et al.'s (2003) Unified Theory of Acceptance and Use of Technology (UTAUT) emphasizes perceived ease of use and effort expectancy as key mediators in digital adoption, which aligns with the concerns raised about platform complexity and usability in this study.

Participants also identified cybersecurity risks, language barriers, and high transaction costs as notable hindrances, consistent with recent regional studies (Fernando et al., 2022; Seneviratne, 2023). These risks, compounded by limited awareness and digital financial skills, contribute to the underutilization of platforms for economic advancement.

On the positive side, the thematic analysis points to several capability enablers that support digital empowerment: access to training, financial literacy programs, localized content, and mobile-based entrepreneurship support. These enablers contribute to tangible outcomes such as freelance income generation, time-saving in transactions, improved communication, and increased participation in e-commerce and service platforms. These reflect similar findings from global studies, including UNCTAD (2019) and Sundararajan (2016), on how "Uberization" can democratize income opportunities.

The conceptual model (Figure 2) developed based on this analysis integrates the following components: Access Enablers: Internet availability, device affordability, and digital infrastructure.

Capability Enablers: Digital skills training, simplified user interfaces, financial education, and language-accessible content.

Economic Outcomes: Job creation, income diversification, improved market access, and skill development.

Barriers: Cybersecurity threats, poor platform design, high data and transaction costs, limited awareness, and socio-linguistic exclusion.

This framework illustrates that digital economic empowerment is not merely a function of technological access but also of contextual support systems, socio-economic capacity, and user-centered design. Importantly, both enablers and barriers are interlinked and cumulative—absence or presence in one domain influences the others. To maximize the potential of digital platforms for inclusive rural development in Sri Lanka, a multi-stakeholder policy response is necessary. This includes investments in digital infrastructure, public-private partnerships for device and data subsidies, and the integration of digital literacy and entrepreneurship modules into rural education systems. Furthermore, platforms must adopt human-centered design practices that address local needs and overcome usability challenges.

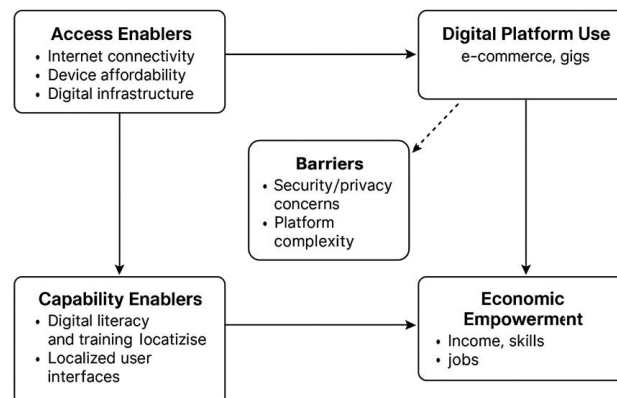


Figure 2: Barriers and Enablers of Digital Economic Empowerment

5. Conclusion

This study investigated the barriers and enablers of digital platform adoption for economic empowerment in rural Sri Lanka. While smartphone (90.7%) and laptop (86.0%) ownership were high, only 81.3% had internet access, highlighting infrastructural gaps. Key challenges included costly internet (26%), device affordability (21%), and low digital literacy (16%). Cybersecurity concerns and platform complexity also hindered usage. Despite these obstacles, many respondents engaged in freelance work, online sales, and communication, benefiting from digital platforms. The study's conceptual framework shows that access enablers like internet availability and device affordability must be supported by capability enablers such as digital literacy and training to maximize outcomes. Significant positive correlations between income and access ($r = 0.59$) and between education and platform usage ($r = 0.99$ for freelance work) affirm the importance of socio-economic factors. Addressing both structural and skill-based barriers is essential to realize the full potential of digital platforms in promoting inclusive rural development.

6. Recommendations

To enhance digital empowerment in rural Sri Lanka, it is recommended to expand affordable and reliable internet infrastructure and subsidize devices for low-income households. Community-based digital literacy programs tailored to local needs should be introduced to improve skills and awareness. Platforms must prioritize user-friendly design and local language support to reduce usability issues. Public awareness campaigns should address cybersecurity concerns and promote safe usage practices. Stronger public-private partnerships are needed to support these initiatives sustainably. These targeted actions will help bridge the digital divide and enable rural populations to fully benefit from digital economic opportunities.

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CIRCULAR ECONOMY FOR SUSTAINABLE DEVELOPMENT

**INVESTIGATION OF THE CARBON EMISSION REDUCTION TARGETS
TOWARDS SUSTAINABILITY -A FOCUS ON 3PL COMPANIES IN SRI LANKA**

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Abstract: This research highlights the carbon emission reduction goals, practices of third-party logistics (3PL) companies in Sri Lanka, their challenges when implementing those practices and their sustainability influence. This study provides actionable insights and recommendations that could apply to other nations, enhancing the understanding of sustainable supply chain operations and addressing a significant research gap. The research employed an interpretivism as a philosophy and an inductive approach to gather qualitative data from seven 3PL companies through fifteen semi-structured interviews, along with literature research from 2019-2024. Thematic analysis was utilised to extract themes and codes from interview transcripts to comprehend the motivations, challenges, and strategies to mitigate environmental impact. The findings reveal fourteen primary themes, including the goal of Carbon Neutrality by 2050, in conjunction with Sustainable Development Goals (SDG) and ESG (Environmental, Social, and Governance) considerations. Numerous companies are beginning to implement basic sustainability practices such as carbon insetting, along with methane control, waste management and carbon offsetting systems. These companies face various challenges in their sustainability efforts, including inadequate stakeholder collaborations, budget constraints, inconsistent market performance, as well as technological limitations and operational challenges. Companies aim to address these issues by proposing initiatives that encourage collaboration with partners, the adoption of technological solutions, incentive programs, and capacity-building initiatives. The analysis highlights how sustainability influences three critical areas: environmental management, economic efficiency, stakeholder collaboration, and digitalisation. This qualitative research, conducted with a limited number of companies, largely concentrates on the Sri Lankan context, making it difficult to identify which specific 3PL companies are employing these strategies. This qualitative study in Sri Lanka centres on carbon emissions within the 3PL sector, examining how these factors impact intellectual research and logistics practices, providing a thorough overview and further recommendations for research.

Keywords: Carbon Emission; Logistics Industry; Sustainability; Third-Party Logistics

1. Introduction

Third-party logistics companies, which account for 10% to 15% of global greenhouse gas emissions, are crucial in shaping global sustainability efforts. However, there is a lack of research on how these companies in developing nations, particularly Sri Lanka and global context, are addressing carbon emission goals. This study examines the approaches Sri Lankan 3PL providers use to minimise emissions within existing constraints. The growth of the sector, particularly in transportation, further burdens already strained infrastructure. Sri Lanka's 3PL companies invest in infrastructure, machinery, and technology to enhance customer experience and operational efficiency. However, they are increasingly expected to adopt greener practices and reduce their environmental impact to meet consumer expectations and regulatory standards. The research investigates the emission reduction targets and sustainability achievements of Sri Lankan 3PL companies, focusing on eco-friendly logistics practices, global initiatives, and climate change mitigation strategies. The study includes interviews with industry professionals to provide an in-depth perspective and aligns emissions reduction goals with operational strategies, offering new insights for industry practice and academic research. The objective of this research is to explore the carbon emission reduction targets, strategies, and obstacles faced by Sri Lankan 3PL companies within the broader framework of sustainability. To ensure clarity and focus, the specific research questions guiding the study have been clearly defined, giving readers a comprehensive understanding of its scope and direction.

2. Literature Review

Carbon emissions, a major contributor to resource depletion and rising temperatures, are significantly impacting the global economy, environment, and cultural dynamics (Ghosh et al., 2020). This literature review explores the economic, social, and environmental impacts of emissions on 3PL companies and their strategies to reduce their carbon footprint.

2.1 Carbon Emissions

Carbon emissions are categorised as direct, indirect, and fugitive emissions (Lai et al., 2022). Companies, often prioritising financial profit over long-term sustainability, contribute to global emissions through their industrial activities, transport, food production, and energy use (Downar et al., 2021). Predictive models suggest a potential 11.5% decrease in global output by 2100 if emissions aren't controlled (Lai et al., 2022). Moreover, as ZariÇ et al., (2023) highlight that governments have enacted laws like the Companies Act 2006 to require annual emissions reporting, but these measures don't guarantee substantial reductions. Climate change is expected to reduce global GDP by up to 2%, affecting urban development, agriculture, and job availability (Lapshin et al., 2023).

2.2 Carbon Emissions on Business Performance

Sustainability is crucial for businesses to boost profitability and competitiveness. The research Visentin et al., (2024), shows that reducing CFP improves brand reputation and financial success, and companies with higher Corporate Social Responsibility (CSR) ratings achieve greater profitability per share, ROI, and brand quality. Downar et al., (2021) Companies focusing on sustainability also experience improved employee engagement and retention. However, the relationship between sustainability initiatives and financial benefits is still debated, with some suggesting that external factors may also play a role (Pan et al., 2024). Decreasing CFP is essential, especially in countries with stringent environmental laws, as strong CSR and corporate governance contribute to financial success. Integrating sustainability practices helps businesses adhere to regulations and secure a competitive advantage (Singh et al., 2024).

2.3 Carbon Emission Reduction Strategies in the Global Context

According to Carvalho et al., (2023), human activities contribute significantly to climate change, causing rising sea levels, elevated temperatures, and glacier melting. Portugal's industries account for 30% of global GHG emissions, emphasising the need for regulation (Fernando et al., 2023). Food systems, particularly meat production, account for 68% of households' carbon footprint (Pan et al., 2024). Vegetarian diets can reduce emissions by lowering meat consumption. The US energy sector's reliance on fossil fuels results in substantial CO₂ emissions (Lapshin et al., 2023). A comprehensive

strategy should include sustainable transportation, reducing meat consumption, and energy-efficient practices. Sustainable urban development initiatives are crucial due to population growth in Asia and Africa (Pan et al., 2024).

2.4 Carbon Emissions Reduction Strategies in the Sri Lankan Context

Sri Lankan 3PL companies are focusing on environmental sustainability through strategic measures like energy-efficient warehousing, sustainable packaging, green technologies, and alternative fuels (Fernando et al., 2023). These strategies have been linked to emissions reductions of around 15% (De Silva et al., 2022). Eco-friendly initiatives, such as improving warehouse layouts, using electric vehicles, and green procurement, support sustainability goals and provide operational benefits like improved inventory management and reduced waste (De Silva et al., 2022). Research suggests these strategies could yield significant emission reductions, potentially reaching 50% (Ghosh et al., 2020).

2.5 Carbon Emissions in the Logistics Industry

The logistics sector faces economic and environmental challenges due to significant carbon emissions. Green logistics, integrating sustainable methods and technologies, promotes waste minimisation, recycling, and renewable energy use (Singh et al., 2024). Implementing these strategies can lead to cost savings, enhanced operational effectiveness, and reduced carbon footprints. According to Karunasena et al., (2019). The industry is under pressure to reduce its environmental impact by up to 20%. A holistic strategy involving energy efficiency, alternative fuel sources, route optimisation, and sustainable supply chain practices is needed for greater sustainability (de Souza et al., 2022).

2.6 Third-Party Logistic Companies (3PL Companies)

3PL Companies play a crucial role in Supply Chain Management (SCM) by offering services like warehousing, transportation, distribution, and inventory management as an external party (De Silva et al., 2022). Their expertise helps businesses optimise their supply chain performance and maintain a competitive advantage (Nawurunnage et al., 2023). The increasing complexity of SCM has led to increased dependence on 3PL companies worldwide, offering benefits like improved operational efficiency, cost reductions, shorter lead times, and reduced transportation expenses (Sürücü et al., 2020). Sri Lankan 3PL companies have invested heavily in technology, workforce, and infrastructure to offer a wide range of services (Gao et al., 2020).

2.7 Carbon Emissions Reduction Strategies in 3PL Companies

Sustainable practices to reduce carbon emissions and enhance supply chain resilience 3PL companies. These include waste reduction, recycling, and the use of alternative fuels and energy-efficient technologies (Nawurunnage et al., 2023). According to Perera et al., (2021) automation is crucial for operational efficiency and resource reduction. Sustainable packaging options, including recyclable and biodegradable materials, also help reduce waste. However, challenges like regulatory constraints, limited funding, and lack of awareness hinder the implementation of these circular economy strategies (De Silva et al., 2022). Government incentives, consumer preferences, and supplier collaborations influence these efforts.

2.8 Carbon Emission Reduction Strategies in Sri Lankan 3PL Companies

3PL companies are embracing sustainability by transitioning to electric and hybrid models, improving warehouse energy efficiency with solar power and LED lighting, and implementing advanced fleet management technologies (Karunarathna et al., 2019). They are also focusing on eco-friendly packaging solutions, minimising waste, and using biodegradable materials. Transitioning to alternative fuels like CNG can reduce GHG emissions by up to 30%, while optimising transportation methods can lead to further emission cuts of 15% (Peiris et al., 2022). Sustainable warehousing techniques can achieve energy savings of up to 25% (Perera et al., 2021).

In Conclusion, this literature review explores research on carbon emission reduction objectives in Sri Lankan 3PL companies, focusing on energy-efficient technologies adopted by successful companies and their impact on the Sri Lankan economy and the global market.

3. Methodology

This study utilised a qualitative approach to assess non-numerical data from 3PL companies in Sri Lanka, focusing on carbon emission goals and sustainability. The research design involved selecting individuals, including logistics managers and sustainability officers, who actively participated in sustainability efforts within 3PL operations. The sample design used a purposive sampling method, and data were collected through interviews using an open-ended questionnaire. The data collected included perspectives from sustainability officers and logistics managers, both in-person and online. The population included all 3PL companies in Sri Lanka, while the sample included seven 3PL companies with fifteen interviews. The research has two main limitations: it is based on a small sample of fifteen interviews, which may not accurately represent the diverse viewpoints in Sri Lanka's 3PL industry, and its qualitative methodology, which is specific to the Sri Lankan context, limits its applicability to different environments or quantitative analyses. The study employs thematic analysis, a systematic six-step approach that encompasses familiarisation, coding, topic generation, review, definition and naming, and the final writing process, to analyse qualitative data derived from transcripts or interviews.

3.1 Data Analysis

Thematic analysis is a method used to analyse data by identifying recurring patterns and themes. This process involves five stages: familiarisation with the data, creation of initial codes, identification of themes, evaluation of themes, and definition and naming of themes. The first stage involves conducting detailed interviews and analysing transcripts to facilitate the analytical process. The second stage involves formulating initial codes, which are then transferred to an Excel spreadsheet for further analysis. The third stage focuses on identifying themes, which are recurring patterns that underscore the dataset's distinctive characteristics. The fourth stage involves reviewing themes and codes to verify their coherence and relevance to responses. The final stage involves the manual definition and naming of themes. The MAXQDA Data Analysis software is used to illustrate the code clouds for this process.

4. Results and Discussion

This section discusses the goals, practices, and challenges faced and how they enhance sustainability in Sri Lankan 3PL companies in reducing carbon emissions, identifying key themes for each.

4.1 Carbon emission reduction goals in 3PL Companies

It shows the two themes identified for CO₂ emission reduction goals in 3PL companies.

4.1.1 Carbon Neutralisation and Net-Zero Carbon Emission Goals

Sri Lankan 3PL companies aim to achieve net-zero carbon emissions by 2050 to balance and absorb GHG emissions, addressing challenges like rising sea levels and global temperatures. Sri Lankan 3PL companies aim to achieve net-zero carbon emissions by 2050, aiming to balance GHG emissions with environmental absorption, driven by rising sea levels and global temperatures.. *“We are having several discussions with the Carbon Climate Fund, one of the government institutions working towards these carbon-neutral processes. So, we are working with them to develop a strategy to become carbon neutral by 2050.”* – Respondent 01. Sri Lankan 3PL companies collaborate with the Sri Lanka Climate Fund to develop strategic plans to reduce carbon emissions by 40% by 2030 and achieve net-zero emissions by 2050. This is achieved through energy-efficient practices, renewable energy use, and green building certifications. Public awareness is also raised about energy-saving initiatives like solar panels, route planning software, and LED lighting, aiming to reduce carbon emissions. *“And we are planning to install a solar panel system as well. That is also ongoing. So, we have already taken the quotations as well. So that is also ongoing.”* -Respondent 01. Research is underway on renewable energy sources, including hydropower, solar energy, and wind energy.

4.1.2 Sustainable Development Goals and ESG Goals

Corporate social responsibility involves a company's commitment to minimising environmental and social impacts, focusing on waste reduction, employee satisfaction, process transparency, and biodiversity preservation. *“When it comes to our ESG strategy, we have targets for emissions, energy, water waste, and biodiversity. Therefore, other than the main energy consumption for GHG, we have water targets and waste targets. Therefore, they are working on those areas as well.”* – Respondent 01. Biodiversity is crucial for disease prevention, climate change reduction, and pollution reduction. Corporate sustainability reporting promotes accountability, transparency, and communication by disclosing environmental, social, and governance performance. Figure 1 illustrates that the code cloud was developed based on MAXQDA Software for emissions reduction goals in 3PL companies.

4.2 Carbon emission reduction practices in 3PL Companies

It shows the three themes identified for CO₂ emission reduction practices in 3PL companies.

4.2.1 Carbon in Setting Practices



Figure 1: Visual representation of coded themes concerning carbon emissions reduction goals

3PL companies are aiming to decrease carbon emissions by implementing solar panel systems and transitioning from gasoline-powered vehicles to electric ones. *“We have around 100 of that equipment. So, we are converting those engine-driven Prime Movers to electrified EV-driven Prime Movers.”*- Respondent 04. Strategies aimed at reducing noise pollution and GHG emissions include reverse logistics, load maximisation, and route optimisation. *“Route planning, Load maximisation, and Reverse Logistics are some of the initiatives we have taken to reduce cargo emissions.”* -Respondent 05. The practice of rainwater harvesting reduces operational expenses and contributes to the preservation of water resources by collecting and storing rainwater. *“And we do rainwater harvesting as well, because in warehouses we can save water. We do rainwater harvesting and wastewater treatment plants.”* – Respondent 07. The wastewater treatment process, which eliminates pollutants and generates recycled effluent, presents a significant challenge in integrating sensory lighting, air conditioning systems, and warehouse design. Strategies for emission reduction are developed, and action is taken in management reports.

4.2.2 Methane Control and Waste Management

Emission reduction strategies are developed and integrated into management reports. *“Yeah, from our perspective, from our company, we were from our side to reduce the footprint of the greenhouse gases. Like CO₂, methane, nitrous oxide, likewise”*-Respondent 03. 3PL companies in Sri Lanka are adopting strategies aimed at enhancing sustainability. They are facilitating the transfer of biochar and methane collection technologies, which contribute to the reduction of GHG emissions and support the development of a circular economy.

4.2.3 Carbon Off-Setting Practices

Individuals or organisations employ carbon offsetting methods to counterbalance their CO₂ emissions by financing projects aimed at reducing emissions. “We have several CSR like we had a mangrove rehabilitation program, and we had two mangrove rehabilitation programs. Then we started coral planting; we did one in Galle, and another one is planned in Unawatuna. Likewise, we have identified several programs to minimise carbon emissions and increase the resorption. Respondent 02.3PL companies have partnered with organisations like the Sri Lanka Climate Fund and CEA to reduce carbon emissions and protect the environment. Figure 2 illustrates that the code cloud was developed based on MAXQDA Software for CO₂ emission reduction practices in 3PL companies.



Figure 2 : Visual representation of coded themes concerning Carbon emissions reduction practices

4.3 Challenges in Carbon Emissions Reduction Practices of 3PL Companies

It shows the four themes identified with challenges faced when implementing those practices.

4.3.1 Lack of Stakeholder Engagement

3PL companies face challenges in engaging stakeholders in reducing carbon emissions due to differing interests and goals, including potential job losses or increased workloads. “We sometimes face challenges when we communicate to our shareholders the changes we make to our processes to establish more sustainable operations.” – Respondent 09. Management is cautious about potential risks, but adopting carbon emission reduction strategies like solar panels and electric vehicles can offer immediate and long-term benefits.

4.3.2 Financial Obstacles

Sri Lankan businesses face challenges in implementing carbon emission reduction initiatives due to high costs, leading to project suspensions, especially in solar energy systems.. “The main challenge is the cost. When it comes to the carbon emission initiatives, it comes with the cost. So, for every project, we must incur some costs. More than 100,000 USD. So, we must get the board's approval.” – Respondent 03. Market price fluctuations and cost transfer burdens hinder long-term strategies and precise expenditure predictions, especially in trading carbon credits and offsets.

4.3.3 Technological Boundaries

Sri Lanka's electric vehicle transition faces challenges due to limited charging infrastructure, affecting operational efficiency and charging times. “Even Sri Lanka doesn't have a lot of charging stations. When we transport goods, we also need charging stations all over the country. We plan to implement 1st charging stations and then to bring on EV vehicles.” – Respondent 03. The absence of locally manufactured products also hinders advanced technology integration, forcing companies to import or produce items, potentially causing operational disruptions and increased costs.

4.3.4 Operational Barriers

3PL companies in Sri Lanka face challenges such as obsolete equipment, GHG-emitting vehicles, and limited access to technology. *“We tried to implement solar power, but it failed because of the wind situation. Here, the wind power is not reliable. So, we can't generate wind energy in solar ports.”* – Respondent 03. Despite advanced technologies, they face environmental factors like erratic wind patterns and factory production fluctuations, disrupting their processes. Figure 3 illustrates that the code cloud was developed based on MAXQDA Software for challenges of carbon reduction practices in 3PL companies.



Figure 3 : Visual representation of coded themes concerning Challenges of Carbon Reduction Practices

4.4 How carbon emissions reduction enhances the sustainability of 3PL Companies

It shows the four themes identified in how CO₂ emission reduction enhances sustainability in 3PL companies.

4.4.1 Environmental Management

3PL companies are reducing their carbon footprint by implementing sustainable practices like solar energy systems, electric vehicles, wastewater management, and rainwater collection. *“As a company, we believe that implementing earlier mentioned strategies will impact the sustainable operations.”* – Respondent 04. They are also optimising warehouse operations, using energy-efficient machinery, fostering a circular economy, monitoring emissions, and implementing effective waste management methods, thereby expanding their customer base and improving operational efficiency.

4.4.2 Economic Effectiveness

3PL providers can reduce fuel expenses, boost profitability, and meet environmental standards by streamlining operations, optimising workflows, and improving communication. *“By implementing preventive maintenance, we were able to reduce the maintenance cost and hence assist the sustainability.”* – Respondent 06. This leads to increased productivity, efficiency, and reduced travel times. Additionally, it simplifies inventory management and incorporates green logistics practices, reducing risks and boosting employee motivation.

4.4.3 Stakeholders Collaboration

Transparency in environmental performance boosts trust, investor relations, talent attraction, and customer attraction. *“We are providing regular updates to our stakeholders. We are providing the data that we have gained from our projects to our stakeholders. And once we completed the project, we notified our stakeholders that we had completed this project.”* – Respondent 08. 3PL companies can appeal to environmentally conscious clients, strengthen customer loyalty, and collaborate with industry partners for joint initiatives.

4.4.4 Digitalisation

Automation technologies like route optimisation and inventory management can reduce waste and enhance operational efficiency. Advanced logistics solutions, supply chain traceability, and renewable energy use can reduce carbon emissions, improve brand reputation, and ensure regulatory compliance. Figure 4 illustrates that the code cloud was developed based on MAXQDA Software for how CO₂ emissions reduction enhances sustainability in 3PL companies.



Figure 4: Visual representation of coded themes concerning carbon emissions reduction to enhance Sustainability

4.5 Discussion

The study examines Sri Lankan 3PL companies' carbon emission reduction goals, current practices, challenges, and their contribution to sustainability. The text discusses the environmental impact of carbon neutralisation, net-zero emissions, sustainable development, and ESG goals, as well as the challenges they face (Singh et al., 2024). The primary goal is to achieve net-zero emissions by 2050 to combat global warming and the GHG effects (Pallege et al., 2023). Companies are implementing strategies to reduce emissions, with the International Maritime Organisation aiming to decrease shipping carbon emissions by 40% by 2030 (Lai et al., 2022). Sri Lankan 3PL companies can contribute to lowering carbon emissions by complying with regulations and implementing energy-efficient practices (Dahlmann et al., 2019). CSR aims to reduce waste, lower carbon emissions, safeguard employee welfare, and enhance transparency in business operations (Scrucca et al., 2021). Corporate sustainability reporting fosters accountability and transparency. Preserving biodiversity is crucial for mitigating pollution, alleviating climate change, and preventing disease (Ramos et al., 2022). The findings align with earlier research on carbon reduction strategies within the logistics sector. For instance, studies by Pan et al., (2024) and Nawurunnage et al., (2023) have demonstrated the effectiveness of load maximisation, route optimisation, and vehicle electrification in reducing transportation-related emissions. Furthermore, the work of Lapshin et al., (2023), highlighted the importance of renewable energy in decarbonizing logistics operations, integrating solar energy in 3PL companies, and the need for circular economy principles in waste management, resource efficiency, and optimal warehouse space utilization in 3PL companies (De Silva et al., 2022). While methane capture and control methods are not yet prevalent among Sri Lankan 3PL companies, Pallege et al., (2023) biochar production and landfill gas recovery have shown significant potential in reducing methane emissions, aligning with the growing literature on nature-based solutions for climate change mitigation, such as mangrove restoration and reforestation (Premkumar et al., 2021). The study highlights the increasing pressure on organisations to adopt environmentally sustainable practices to remain competitive (Nayal et al., 2021). This highlights the necessity of targeted interventions like government incentives, capacity-building programs, and collaborative frameworks to tackle challenges and facilitate the transition to low-carbon logistics in Sri Lanka (Longoni et al., 2019). The study also supports previous research that emphasises the importance of environmental management in ensuring the long-term sustainability of logistics operations (Kumar et al., 2021). Energy-efficient strategies, renewable energy integration, and sustainable SCM are all crucial for reducing carbon emissions and enhancing operational efficiency described by Pan et al. (2024). The study Marzuki et al., (2024) and Longoni et

al. (2019) also emphasise the importance of stakeholder collaboration in addressing environmental challenges within supply chains (Nayal et al., 2021). The study emphasises the significance of digitalisation in enhancing logistics operations and minimising environmental impacts, suggesting a targeted approach to Sri Lanka's transition to low-carbon logistics, which includes digital transformation, stakeholder collaboration, economic efficiency, and environmental management.

5. Conclusion

The study explores Sri Lankan 3PL companies' efforts to reduce carbon emissions and adopt sustainable practices through qualitative methods, stakeholder interviews, and literature analysis. It emphasises the objectives of Carbon Neutralisation, Net-Zero Carbon Emissions, SDG, and ESG criteria. Strategies employed include carbon offsetting, methane management, waste management, and carbon insetting. The study recommends solar energy, electric vehicles, wastewater treatment systems, rainwater harvesting, energy-efficient lighting, waste minimisation, recycling initiatives, and waste segregation practices. When considering Policy Implications, this study suggests that Sri Lanka's 3PL sector needs a comprehensive approach to reduce carbon emissions, including legislation, industry standards, and strategic business plans. The government can offer green certifications, tax incentives, and emission thresholds. Companies should focus on optimising operations, improving fuel efficiency, and exploring alternative energy options. However, challenges like inadequate infrastructure and corporate commitment hinder significant emissions reductions. Likewise, the study is limited to the Sri Lankan context; however, it can expand to a global context further. Future investigations should adopt a quantitative methodology to further these strategies, as the current study utilised a qualitative approach as future research. The objective is to support Sri Lankan logistics companies in adopting sustainable supply chain management, enhancing awareness of climate change, and attaining enduring sustainability.

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ICSD 146

ADVANCING CIRCULARITY IN THE CONSTRUCTION SECTOR: A SYSTEMATIC REVIEW OF INNOVATIVE PRACTICES, DIGITAL TECHNOLOGIES, AND POLICY FRAMEWORKS FOR SUSTAINABLE RESOURCE MANAGEMENT

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Abstract: In construction activities, it is estimated that it contributes to the usage of 40-60% of raw materials that are extracted globally and dispose of about 30% of wastes, and therefore, it is particularly sensitive and significant to resource efficiency. Although 95% of the Construction and Demolition Waste (CDW) is down-cycled up to 50% of material consumption reduction can be achieved through the reuse and recycling of 80% of (C&D) waste. Circular Economy (CE) in construction thus seeks to minimize resource use, find ways of using a particular resource more than once and also find ways of recovering and reusing waste resources. Nevertheless, the fulfilment of this potential is still partial and there are conspicuous gaps relating to the implementation of CE principles and advanced digital technologies for enhanced resource utilization, waste management and reduced environmental consequences. Aim of this study is assess the CE practices and identify the challenges of CE implementation and develop comprehensive policy framework for sustainable CE practices. This review followed the PRISMA method criteria and included English 25 studies from the Google Scholar and ResearchGate, Scopus databases that were published between 2015 and 2024. Recyclable Foam-heat insulating brick Compared with concrete heat-insulating bricks, it reduces CO₂ by 48.7 %. Opportunities include improved recycling and reuse, including waste concrete aggregates, fly ash in concrete and bricks, advanced materials like cementitious glass composite bricks. In addition, implementing Building Information Modelling (BIM) and radio frequency identification (RFID) with Industry Symbiosis (IS) with GIS and agent-based modeling leads to better material tracking and control, speaking about the issues of downcycling. Combination of elements in the circular economy and sustainable solutions has greatly reduced the environmental impacts of construction and created a more resilient and resource-efficient industry. However, the adoption of measures for bringing down barriers to implementation needs greater stakeholder engagement, political reinforcement, and legislation to facilitate the transition to sustainable construction practices.

Keywords: Circular Economy; Construction sector; Resource efficiency; Waste management; Sustainability; Digital advancement

1. Introduction

1.1 Background of the study

The Architecture, Engineering, and Construction (AEC) industry is a key contributor to environmental destruction, which includes 40-60% of the total world raw material extraction and, independently, 40-50% of CO₂ emissions (Schützenhofer et al.,2022). Further, Construction and Demolition (C&D) wastes account for almost 33 percent of total waste produced in the European Union.. The evolving construction sector is now global, having played major roles in economic, social, and environmental indicators of sustainability in both developed and developing countries. It is deeply involved in the development of really powerful activities marked by extreme positive and negative influences on sustainability such as economic growth, social conditions, and environments (Sáez et al., 2019). One of these positive contributions is Gross Domestic Product (GDP) growth, job creation, and building various types of constructions and economies to meet human needs. Nevertheless, construction activities have equally caused creating waste, greenhouse gas emission, noise pollution, and dust, all of which pose adverse effects on environmental sustainability (Smol et al., 2015).

1.2 Current challenge

Demolition of a construction product marks the end of life for that product and usually results in the different types of waste generated as follows: wood, concrete, metal, bricks, plastics, gypsum, roofing shingles, and glass, plastic, solvents, asbestos and excavated soil (Colangelo et al.,2020). It is a common understanding that the amount of waste arising out of project demolition is far more than that which will come in from the processes of building a new project. Urbanization and urban regeneration produce enormous amounts of (C&D) waste all over the globe and 95% of the C&D Waste is down-cycled without effectively material recovered (Yu et., 2021). For developed economies, the construction industry tends to consume about 25-30% of total solid waste disposal in general (Lu et al., 2017) However, the best planning and management in project demolitions can give the lowest possible levels of hazards: for instance, recycling as much as possible of the dismantled materials along the chain of material manufacturing. It is important to consider life cycle thinking approach that means C&D waste should be managed from the designing stage to disposal stage.

1.3 Important of circular economy in construction sector

Circular Economy (CE) provides additional opportunities for business, which are predicated on overturning the traditional linear use of materials and replacing it with a more sustainable efficient and circular alternative (Yu et al., 2021). It's a sustainable concept geared toward reducing, reusing, and recycling, thereby conserving material value for as long as possible from an economic and environmental standpoint without overburdening society with the extraction of the primary natural resources with almost 2.6 billion tons natural aggregates is produced and utilized every year only in Europe construction sector: (Luciano et al., 2018). It is crucial for incorporating new innovative approaches in 3R perspective, digital technology connect with circular economy approach, life cycle thinking approach for achieve sustainable construction sector through incorporate CE and waste management (Gálvez-Martos et al.,2018).

1.4 Advancement in sustainable circular economy technologies

Table 01: The Circular economy practices and their benefits

Material/ Technology	Description	Benefits	References
Recyclable foam heat insulating brick	100% recyclable brick produced using waste oyster shells with geopolymer technology	Compared with concrete heat-insulating bricks, it cut-offs CO ₂ by 48.7 %	Shao et al., 2024

Cementitious–glass composite bricks (CGCBs)	Innovative product made by using recycling glass waste (78%) and PET-G (8%)	12% lower thermal conductivity and a 17% lower specific heat promote low CO ₂ emission	Malek et al.,2024
Asphalt recycling	substitution of the raw-mix for cement clinker	40% - 80% of asphalt waste can substitute raw material in asphalt hot mix	Lederer et al., 2020; Mantalovas & Mino., 2019
Clay-fly ash composite brick	Incorporate fly ash from incineration plats with clay	Substantially reduce demand in clay mining, environmental impact, increase resource optimization	Ncube et al., 2021;

While the application of the circular economy concept together with innovative technologies like chemical recycling, sensor technology, digital advancement and upcycling present a more suitable strategy in the case of resource optimization and waste in construction projects and helping to reduce the effects on the environment are the factors in support of the concept (Meliha et al.,2019). For example, fly ash from incineration of sewage waste and natural clay in the construction of building materials following the circular economy standards and sustainability (Ncube et al.,2021).

1.5. Purpose, Scope and objectives of the Review

This review seeks to assess and identify suitable circular economy practices and digital advancement technologies that may potentially be incorporated in circular economy in construction sector in order to optimize resource efficiency, reduce environmental impact. It also aims to identified challenges for circular economy practices implementation and develop comprehensive framework to overcome identified challenges for promote sustainable constructions. Specific objectives as follows;

1. Evaluate and Determine Innovative Practices and Technologies: Assess the most appropriate materials and digital technologies for resource optimization, waste management and emission reduction in the construction industry.
2. Compare Sustainable Practices: Compare various sustainable circular economy practices and technologies in terms of their effectiveness in reducing CO₂ emissions, advantages and disadvantages, and applicability in different construction environments.
3. Develop Comprehensive Framework: Identify challenges in circular economy practices implementation and develop policy framework for sustainable construction sector.

1.6. Research Significance

Analysis of circular economy practices and digital advancement technologies in construction sector critically assess this research based on its capability of globally increase the resource optimization, waste management and decreasing environmental by emission reduction. Through examination of several practices and review of the results of such practices, this research will aspire to inform construction biased policies as well as engage in enhancement of environmentally sound procedures, which will lead to the enhancement of the construct resilience (Shao et al.,2024; Malek et al.,2024).

02. Methodology

This review based on a PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework is used for a selection of the articles concerning sustainable construction and green building techniques. The proposal of the review is to provide an elaborative analysis of developments in these domains based on 25 articles published in the period between 2015 - 2024.(Figure 1).

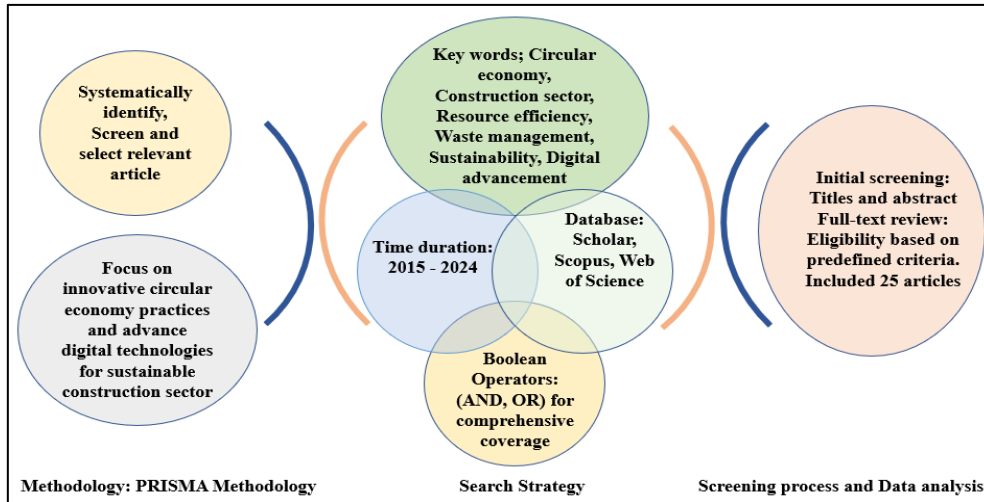


Figure 1: Detailed outline for conducted systematic review using the PRISMA methodology for the review

This review follows the PRISMA guideline to present a systematic analysis of CE principles integration with digital technologies into the construction industry. The targeted keyword searches in Google Scholar, ResearchGate, and Scopus were used to identify English-language articles published from 2015-2024, assuring complete coverage. A comprehensive two-stage screening process based on title/abstract and full-text review was employed, focusing on studies related to CE practices and digital applications (Lederer et al., 2020; Luciano et al., 2018). Data extracted regarding the methodology, findings, and conclusions were assessed for quality and potential bias. The trends highlighted during the subsequent analysis, the comparison of the developments, and the framing of policy guidelines would encourage sustainable construction; hence, the entire work is presented transparently, following PRISMA guidelines.

03. Results and Discussion

3.1 Strategic approach in circularity in construction sector

Table 02: Impact of circular economy innovation & technology in Construction

Key Point	Important Findings	Explanation of Influence	References
Waste bricks and concrete aggregate recycling approach	used as substitute for natural aggregates	It is sensitive for transportation distance while minimum environmental benefits	Fořt & Āerný, 2020; Smol et al., 2015; Colangelo et al., 2020
	As partial replacement of cement	20% weight of cement can be replaced with good performance and 25% replacement can be achieved	
	As alkaline activator	It induces almost 48 MPa compressive strength at an addition of about 10% Portland cement and almost cuts 50% CO ₂ than conventional concrete.	
Styrofoam reuse and recycling approach	Used for insulation backfill, light weight concrete, water proof insulation, soil improvement	Fully recyclable construction waste	Ferek et al., 2016

Material flow analyzing of C&D waste	Waste hierarchy for reduce, reuse and recycle C&D waste	Consumption of construction mineral reduced by 32%	Lederer et al.,2020; Luciano et al.,2018
Disassembly and Deconstruction Analytics System (D-DAS)	BIM-based tool enabling real time design assessments, alternative material choices, reduce landfill dependency	Enhance material recovery, minimize C&D waste generation	Akanbi et al.,2019
Recycle concrete aggregate-based industry Symbiosis	Industry Symbiosis (IS) combining Agent-Based Modeling (ABM) and Geographic Information Systems (GIS)	Enhance multiple stakeholder collaboration, supply chain management in construction sector	Yu et al.,2021

Recyclable Foam-heat insulating brick Compared with concrete heat-insulating bricks, it reduces CO₂ by 48.7 % and save an economic price of 451.15 yuan/brick (Shao et al.,2024). With respect to construction and demolition waste, recycling workability has implemented a number of techniques whereby replacement might be used for natural aggregate; waste bricks statistically perform well in replacing up to 20% of the weight of cement; and thus, distance sensitivity might act against environmental advantages (Fořt & Černý,2020). Waste bricks, if crushed, can further be considered as an alkaline activator, achieving almost 48 MPa compressive strength with a small proportion of Portland cement and, at the same time, reducing CO₂ emissions by about 50% as that of conventional concrete (Fořt & Černý,2020). Styrofoam materials are entirely recyclable as construction waste and can be used in the form of insulation backfill, lightweight concrete, waterproof insulation, and soil improvement (Ferek et al., 2016). The material flow analysis conducted on C&D waste also recommends the waste hierarchy of Reduce-Reuse-Recycle, which might cause a reduction of the consumption of construction minerals by up to 32% (Akanbi et al.,2019). previous research showed Steel structures are rated as having the most deconstructability (DAS = 0.94, 93% reusable materials), followed by timber (DAS = 0.61, 65% reusable), while concrete is the lowest (DAS = 0.57, 42% reusable) due to damage sustained during demolition. The study investigates the possible utilization of Recycled Concrete Aggregates (RCA) to replace Primary Concrete Aggregates (PCA) to address the financial constraints along-the-fractured construction supply chain. Agent-Based Models (ABM) integrated with Geographic Information Systems (GIS) (Yu et al.,2021) simulate dynamic supply-demand of RCA while revealing collaborative information systems.

3.2 Material substitutions & Quantified Benefits

Table 03: Conventional Materials Substitutions & Quantified Benefits for Environment and Economy

Material	A Suggested Substitution	CO ₂ Reduction	Economic Benefit	Source
Concrete bricks	Recyclable foam heat-insulating bricks	48.7%	¥451.15 saved per brick	Shao et al., 2024.
Traditional clay brick	Clay-fly ash composite brick	Reduced clay mining; long-term cost savings	Higher durability	Ncube et al., 2021.
Concrete mix (ordinary)	Waste brick as cement replacement (20%)	25% less CO ₂ (up to 48 MPa strength)	Decreased demand for clinker	Fořt & Černý, 2020.

Virgin glass	Cementitious-glass composite bricks	17% less CO ₂	Better thermal insulation.	Virgin glass

3.3 Technological advancement

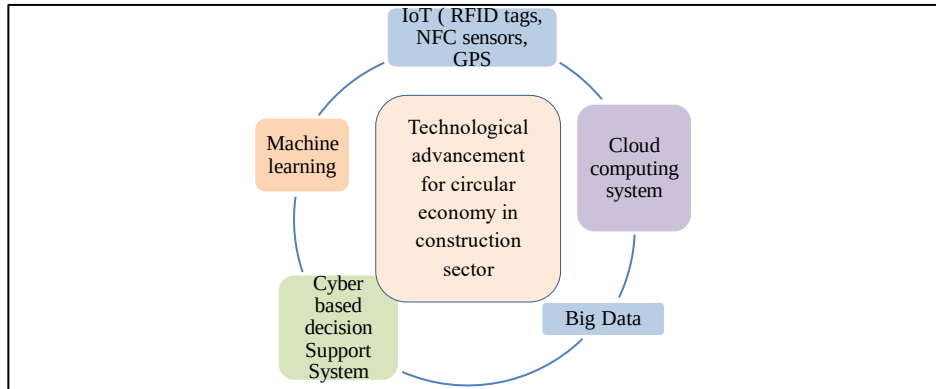


Figure 02: Application of digital technology in Circular economy

Digital technology help to enhances construction waste management by being more efficient, data-driven, and harmonized with the principles of a circular economy approach. Real-time tracking of construction materials, waste streams, and logistics by IoT technologies like RFID tags, NFC sensors, and GPS sensors will enhance waste collection processes (Turskis & Šniokienė, 2024), then it increases resource efficiency. These technologies enable the ongoing monitoring of material flows, it allows effective management of reusable and recyclable components in construction sector. Cloud computing supports the storage and sharing of waste management data among the stakeholders, thereby enabling real-time collaboration on decision-making (Çetin et al., 2021). By ensuring that information is available all the way from waste generation to recycling and recovery of value, cloud-based systems support circular economy strategies by promoting transparency and better resource management across the construction lifecycle. Big Data contributes to waste minimization by investigating trends of waste generation, site-specific distribution, and socio-economic factors affecting construction waste (Nobre & Tavares, 2017). Through geographic and material flow integration, Big Data underpins predictive modeling that aids construction firms in achieving maximum waste minimization, higher material recovery rates, and better deconstruction planning (Akanbi et al., 2019). Cyber-based Decision Support Systems (CDSS) give critical support to policymakers and practitioners in designing, monitoring, and optimizing construction waste management schemes (Zhang et al., 2019). It also provides the modeling of scenarios to aid decision-makers in comparing the effectiveness of different waste management strategies on various environmental impacts such as carbon credit and their adherence to regulations that include circular economy principles. AI techniques, ranging from machine learning to deep learning systems, enable even greater efficiencies by elucidating material usage patterns, projecting optimal reuse and recycling avenues for that material, and automating sorting operations. In construction waste management, AI technologies enhance decision-making with timely material evaluation, diverting waste from landfill and advocating for the sustainable use of resource.

3.4 Comprehensive framework for overcome challenges in sustainable energy transition practices

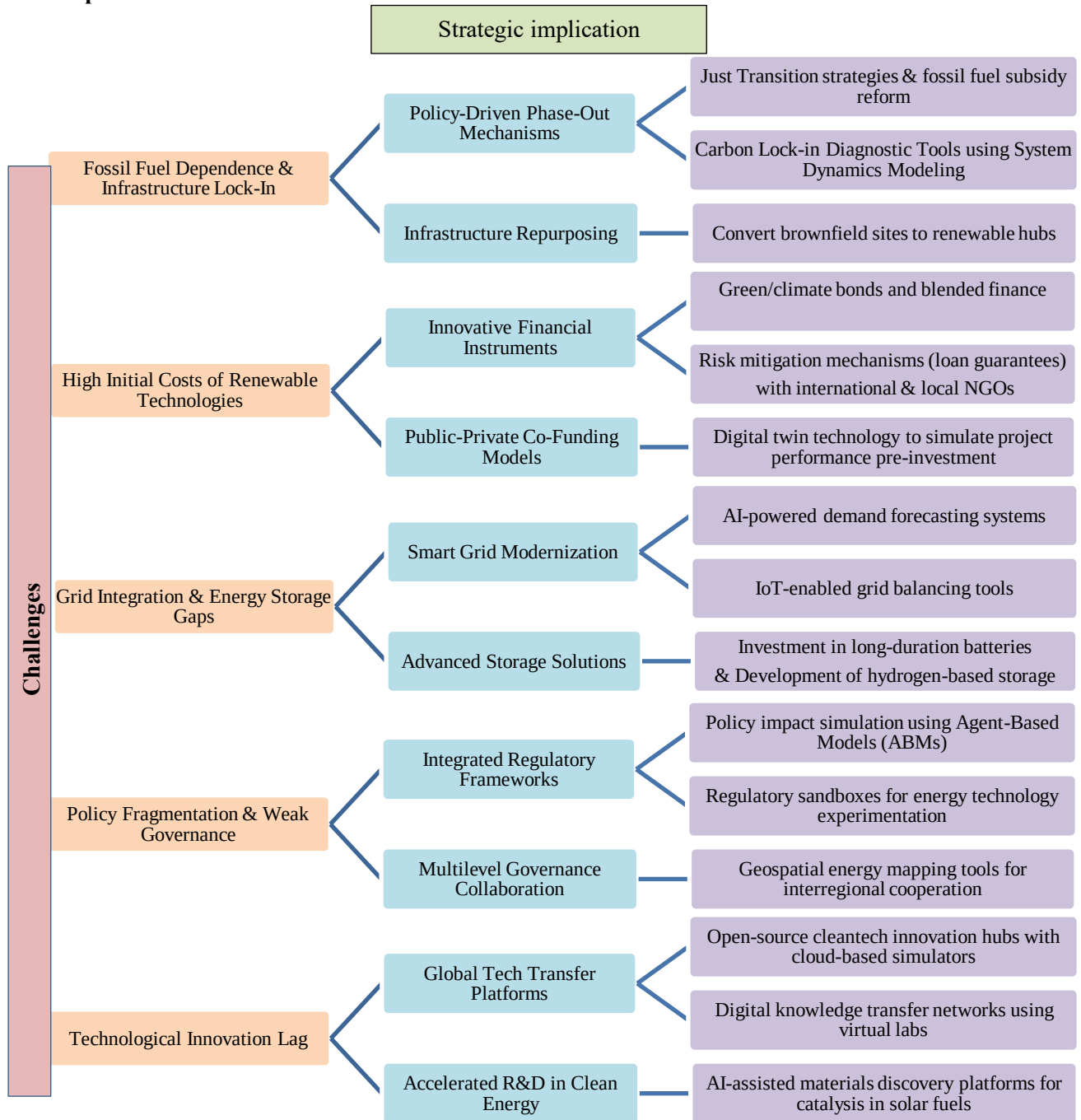


Figure 03 :Comprehensive framework for sustainable circular economy in Construction sector (Meliha et al.,2019; Huang et al,2018 ; Zhang et al.,2019; Janeczek et al., 2019)

Challenges that face the progressive shift toward a circular economy in construction include antiquated waste management procedures, money problems, inertia against change, and inadequate enforcement of regulations (Zhang et al.,2019). Nevertheless, a multi-dimensional approach to a sustainable future would be the way forward. The contemplative industry could equip itself with knowledge and, therefore, adopt smart C&D waste management through innovative technology (Cloud computing system, RFID, GPS tracking system (Çetin et al.,2021; Zhang et al.,2019) institutional collaborations, and improved public-private partnerships. Harnessing R&D and resilient supply chains with the long-term

profitability model will foster innovative ideas while providing relief to the economy through financial incentives like low-interest loans, tax rebates, and subsidies. The regulatory framework itself should be an improvement from what currently exists; therefore, it should incorporate life cycle thinking, material passporting, and solidly enforced mechanisms that would steer the industry toward circularity (Plociennik et al., 2022). There is a need for a thorough change of mindsets to complement policies and infrastructures—to that end, awareness campaigns, stakeholder engagement, and standardized systems of certification will help rewrite the narrative of construction from a linear, wasteful story, to one of sustainability that aims at regeneration. Finally, if the future of construction is not just an attempt to build structures, it is about building a smarter, greener, and more resilient world.

04. Structured Implementation Plan (Short-to-Long Term Actions)

Table 04: Structured Circular Economy Implementation Roadmap in Construction

Timeline	Action	Purpose	Barrier Addressed
Short-term (1–2 yrs)	Conduct lifecycle analysis & pilot studies on recycled materials	Identify viable CE materials	Knowledge gap
Mid-term (3–5 yrs)	Integrate BIM-RFID-AI platforms in waste tracking	Enable digital transformation	Technology cost & training
Mid-term (3–5 yrs)	Offer policy incentives (tax benefits, green loans)	Encourage CE investments	Financial limitations
Long-term (5–10 yrs)	Institutionalize Material Passports & CDSS	Ensure regulatory compliance & transparency	Regulation and awareness
Long-term (5–10 yrs)	Develop local CE standards & certification systems	Foster consistent national adoption	Lack of enforcement

(Meliha et al., 2019; Plociennik et al., 2022; Zhang et al., 2019)

05. Future Direction

Furthering the CE discourse in construction entails investigating themes under-represented in the literature. Circular practices in informal construction sectors in low-income countries, where informal labor dominates but data are scarce, are one of them (Huang et al., 2018). Another critical aspect is the local adaptation policy framework environment that should be tailored to different climatic, economic, and cultural backgrounds to ensure meaningful CE uptake (Gálvez-Martos et al., 2018). Some research areas with a promising future further grasp and develop CE strategies at the global level are decentralized CE systems, material passports in rural construction, and behavioral incentives for adoption.

06. Conclusion

Incorporating principles of circular economy within the construction sector offers a transformative opportunity to reduce environmental degradation, waste, and resource efficiency. Very large raw material consumption and CO₂ emissions stem from the construction industry; therefore, the transition of the construction industry must move away from linearity ('take-make-dispose') and towards

regenerative practice, including recycling, reuse, and new material solutions. Digital technology innovation applications in AI, IoT, and blockchain support smarter resource management and waste minimization, thus enhancing sustainability. However, at this moment, large-scale implementation is hindered by barriers due to regulatory gaps, financial constraints, and resistance to changes. A holistic approach incorporating reform policies, financial incentives, and strategic collaboration supported by stakeholder engagements will have to be instituted to clear all these obstacles. Furthermore, life cycle thinking should be integrated with material passporting and Industry 4.0 technologies to increase construction processes' circularity. For years to come, circular construction not only offers tremendous potential for mitigating environmental harm but also for job creation, socio-economic resilience, and actualizing global sustainability aspirations—a journey we must take for the sake of a sustainable and resource-efficient built environment for generations to come.

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ICSD 148

**POTENTIAL, CHALLENGES, AND STRATEGIC IMPLEMENTATION OF
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Abstract: Floating Solar Photovoltaic (FPV) technology presents a viable path for Sri Lanka to reach its renewable energy target of 70% by 2030. Despite growing global FPV adoption, comprehensive assessment for developing nations with extensive water resources remain limited. The objectives of this study were to determine FPV feasibility, economic viability, environmental and social impact, and develop a strategic implementation framework for Sri Lanka. The methodology employed a mixed-methods approach integrating four key dimensions: technical feasibility assessment; economic modeling comparing FPV with ground-mounted systems; environmental impact evaluation; social acceptability analysis; and review of published research papers and news articles on existing implementations. Three existing installations-University of Jaffna, Chandrika-Wewa, and Kiriibban-Wewa were mainly considered. Results, supported by existing data, show that installing FPV across 9.7% (69 km²) of larger perennial reservoir would enable to achieve its 2025 power generation target of 6,900 MW. Existing installations prove that FPV functions effectively through water cooling systems, which boost performance by 10-15%. The cost of establishing FPV systems could exceed ground-mounted systems by 30%. Key findings demonstrate the main implementation obstacles that involve the need for specific anchoring and mooring systems because of seasonal water level changes, wildlife interference, environmental restrictions on water coverage percentage, and social resistance from fishing communities and in culturally important water bodies. The proposed implementation framework consists of three stages: policy development and capacity building during 1-2 years, followed by hydroelectric integration during 3-5 years, before competitive procurement initiates mainstream deployment after 5 years. The integration of FPV with existing hydroelectric infrastructure shows the best potential implementation route because it combines complementary generation patterns with current transmission systems while minimizing water evaporation. The study provides specific implementation strategies to nations with limited land resources and high energy demands through integrated solutions that simultaneously address technical, economic, environmental, and social aspects.

Keywords: Floating photovoltaic; Renewable Energy; Environmental Management; Hydroelectric Integration; Social Acceptance

1. Introduction

The global energy industry is transforming toward renewable power generation because of environmental needs, technological progress and accelerating energy consumption. The power challenges in Sri Lanka require attention because the country needs to produce 70,000 GWh of electricity by 2050 from its current level of 14,000 GWh in 2016. Sri Lanka has joined the Climate Vulnerable Forum as one of its 43 member nations to achieve 100% renewable electricity generation both rapidly and by 2050 at the latest (ADB, 2017). The government aims to fulfill 70% of future energy requirements through renewable energy sources by 2030 (MOE, 2021). Sri Lanka possesses strong solar energy resources, with annual average global horizontal irradiation ranging between 4.5–6.0 kWh/m²/day (Renné et al., 2003). However, the country generated less than 0.01% of its energy from solar power in 2016 (Reuters, 2016). Solar installation capacity subsequently increased to 434 MW by 2021 (IRENA, 2022).

Worldwide floating photovoltaic (FPV) capacity doubles each year, and experts estimate that using FPV to cover just 1% of global reservoirs could produce a total capacity of 404GWp (Essak & Ghosh, 2022). Sri Lanka together with other densely populated countries that possess ample water resources, stands to benefit significantly from this global FPV trend, which helps resolve energy problems while protecting scarce land.

Land availability stands as a primary barrier to establishing major solar facilities in Sri Lanka. The country stands among the most densely populated nations worldwide with 353 people/km² (CBSL, 2021) and its land resources are limited to 40% agricultural use and 30% forest and wildlife protection zones alongside 30% available for other activities (Mapa et al., 2002). The land shortage for solar implementation in Sri Lanka becomes more challenging because 77.4% of the population lives in rural agricultural areas (DCS, 2021). As a solution, Section 2.7.3 provides a thorough evaluation of water resources and their compatibility with FPV system deployment in Sri Lanka.

FPV solves land utilization challenges by establishing solar installations on water surfaces. The technology received its first commercial application in California in 2007 (Vo et al., 2021), before expanding worldwide, particularly in countries with land limitations like India, Thailand, Vietnam and China (World Bank, 2021).

FPV systems generate 10-15% more power than traditional ground-mounted solar installations because water cooling enhances performance while reducing water evaporation and protecting land resources (Cazzaniga et al., 2012). Additionally, FPV systems integrate seamlessly with hydroelectric facilities, boosting hydroelectric output by 65% when covering 10% of reservoir areas (Cazzaniga et al., 2019). FPV implementation in Sri Lanka faces multiple barriers: technological, economic, environmental and social challenges. The anchoring and mooring systems present technical difficulties when operating reservoirs that undergo seasonal water level fluctuations. The financial limitations include expensive capital investment and weak economic motivation. Research recommends that reservoirs should keep their surface coverage between 10-30% (Mathijssen et al., 2020) and 40-60% (Bhattacharya et al., 2024) to protect ecological systems. Shading aquatic ecosystems leads to reduced oxygen levels as one of the potential impacts. The resistance of different community groups creates social challenges through their concerns about fish yields and irrigation water availability alongside their fears about reservoir water contamination and their cultural attachment to historically significant water bodies.

The human rights commission of Sri Lanka received complaints from both farmers and freshwater fishermen who opposed the planned two 1 MW FPV plant construction at Chandrika Wewa and Kiribban Wewa in Embilipitiya (Economynext, 2024a). Environmentalists have directed their protests at the Sri Lanka Sustainable Energy Authority because they claim the authority failed to follow proper preparation steps for installing these facilities (The Morning, 2024). Also a pre-feasibility study that took place in 2018 at Bandaragama to deploy an FPV faced opposition from local authorities along with

residents because they feared the tank which irrigates cultivable land would be negatively affected (Solheim, 2018).

This study evaluates the implementation potential of FPV in Sri Lanka by investigating technical, economic, environmental, and social factors. The analysis presents solutions to address deployment challenges while optimizing benefits for FPV systems within Sri Lanka's specific geographical and socio-environmental context. This research expands the existing knowledge about FPV deployment in developing countries with substantial water resources by implementing an integrated framework that simultaneously evaluates technical feasibility, economic viability, environmental impacts, and social considerations, rather than assessing these factors sequentially.

2. Literature Review

2.1 Evolution of FPV Technology

The commercial use of FPV systems gained significant traction since 2010 when the first commercial installation was set up in California in 2007 to deal with the evaporation of irrigation tanks (Vo et al., 2021). Global FPV has been growing fast, reaching 1.1 GW in 2018, up from 10 MW in 2014 (Gamarra and Ronk, 2019), and Japan dominates half of the global market by 2015 (Abid et al., 2019). Sri Lanka and other low-middle income states have considerable capacity to generate solar power on the basis of geographical location (World Bank, 2020; World Bank, 2021).

2.2 Technical Aspects of FPV Systems

i. System Components and Design

FPV systems use simple photovoltaic components but they need water-friendly structure with pontoons (polymer floating devices), underwater cables, mooring systems, electrical connections, PV modules, and inverters (Ranjbaran et al., 2019). High-Density Polyethylene (HDPE) is used in floating platforms because it is highly durable, UV resistant and it is recyclable (Wells, 2011). The anchoring systems use stiff perimeter bracings against the dead and lateral wind or wave loads (Ferrer-Gisbert et al., 2013), and the electrical components involved have to resist significant mechanical stresses, abrasion, high temperature, and long service life (Sharma et al., 2015).

ii. Performance and Efficiency

The operation of FPV systems brings distinct characteristics that differ from traditional ground-based installations. Tracking systems enhance power generation on floating structures by reducing environmental wind effects that cause azimuth angle deviations according to Rosa-Clot and Tina (2020). The systems improve output by 24% while using just 1% of photogenerated energy.

The efficiency of solar cells benefits from cooler temperatures yet water's natural cooling effect on FPV systems remains inconsistent because of system design aspects and basin characteristics according to Dörenkämper et al. (2021) and Peters and Nobre (2022). Therefore researchers investigate active cooling methods despite limited existing studies showing promising results. Researchers in Southern Italy evaluated the financial viability of different FPV designs by studying how water both cooled systems and contributed to active cooling mechanisms and tracker systems while recognizing decreased water evaporation because of module shading (Tina et al., 2023). By 2030 the solar market will have more than 50% penetration of bifacial modules according to VDMA (2021). The low reflective properties of water make these modules traditionally unfit for FPV applications (Saini et al., 2023). The efficiency levels of FPV systems surpass those of traditional land-based systems according to current research findings. The research conducted by Liu et al. (2017) established that FPV panels function at temperatures that are 3.5 degrees Celsius cooler. The developers predict that these systems could achieve 50% improved performance under ideal operating scenarios specifically in tropical zones like Sri Lanka (Sudhakar, 2019). The implementation of water pumps as active cooling systems uses only 0.25% of generated energy to achieve approximately 20% efficiency enhancement by increasing light absorption and reducing thermal drift (Cazzaniga et al., 2017).

2.3 Advantages of FPV Systems

Evaporation control emerges as a crucial benefit for water conservation. The Turkish reservoirs and lakes lose 6.8×10^9 m³ per year and the Segura Basin in Spain has lost more than 6.0×10^7 m³ (more than 8 percent of the irrigation water) and the agricultural reservoirs in Queensland lost 1.0×10^9 m³ (40 percent of their capacity) to evaporation (Gokbulak and Ozhang, 2006; Alvarez et al., 2008; Craig et al., 2005). FPV technology minimizes evaporation by 70 percent and produces 6 percent more energy (Mittal et al., 2017; Majid et al., 2014) and cools the temperature of water bodies across their reach (Durkovic and Djuricic, 2017). In very populated countries, land shortage is a significant challenge to traditional renewable energy. FPV systems compensate this fact through the use of water surfaces, minimizing the costs of site preparation, construction of foundations, and security infrastructure (Goswami et al., 2019). Combinations with current hydroelectric stations open up great prospects, and the studies of 20 major hydroelectric plants in the world have shown that the installation of FPV on 10 percent of the surface of the reservoirs increases hydroelectric power by 65 percent and allows supporting transmission corridors, synchronizing power cycles, and improving the clarity of water due to the suppression of algae growth (Cazzaniga et al., 2019).

2.4 Challenges and Limitations

2.4.1 Technical Challenges

The technical barriers are low record of extended testing, poor industry standards, and unpredictable performance in various environmental conditions (Sudhakar, 2019). The anchoring and mooring systems used in deep reservoirs with seasonal variations in the water level are also seriously challenged by the wave forces that may displace the floating structures necessitating special engineering and high costs (Akole and Jadhav, 2018). This is a major problem to the deep reservoirs of Sri Lanka that have high seasonal fluctuations (Saase et al., 2020). Water proximity necessitates strong insulation, weatherproofing, corrosion-resistant components, and specialized maintenance procedures.

2.4.2 Environmental Considerations

FPV systems provide multiple environmental advantages to the ecosystem yet they present some potential ecological challenges. Water body shading constitutes the main environmental concern because it decreases aquatic plant photosynthesis and leads to potential ecosystem changes. The implementation of FPV systems on fishing ponds proved to decrease fish production levels through diminished oxygen availability according to research by Château and the team. The level of ecological damage depends heavily on the amount of area covered by FPV systems. Tests show that fish production can sustain about 70% of its normal levels when solar panels shade up to 60% of water areas (Château et al., 2019). The installation of FPV systems requires attention to chemical substance seepage from components and wildlife habitat disruption specifically in locations where water bodies function as home to migrating birds and endangered species. According to Durkovic and Djuricic (2017), who studied Skadar Lake in Montenegro, protected habitats require detailed environmental assessments and strict mitigation measures.

2.4.3 Socioeconomic Barriers

The acceptance of FPV systems faces major hurdles when implemented in areas where people earn their living from water resources. The members of fishing communities consistently voice their worries about diminished fishing yields. The pre-feasibility study conducted in Bandaragama village in Sri Lanka faced opposition from local authorities and residents who were worried about irrigation impacts (Solheim, 2018). Uncertainties in the economy create obstacles that restrict widespread acceptance of FPV systems. The research on FPV system cost analysis remains comparatively limited compared to other renewable technologies including offshore wind according to Mittal et al. (2017). The cost of FPV systems has been estimated to be 30% higher than conventional land-based solutions according to Ferrer-Gisbert et al. (2013) but Ranjbaran et al. (2019) found that total expenses become equivalent when analyzing land acquisition expenses.

2.5 Global Implementation and Case Studies

Global organizations use FPV technology to gain insights about performance strategies as well as best practices. The Japanese have adopted FPV technology at the highest rate because they manage their scarce land resources effectively. FPV technology has found its applications across China alongside South Korea Taiwan and various parts of Southeast Asia. South Korean engineers designed specific FPV systems which resist freezing effects caused by water conditions (Kim et al., 2019). Taiwan proved that combining aquaculture with power production leads to economic success through its findings that 60% pond coverage produces 130 MWh/yr which generates \$20,150 USD/yr without significant fish production decreases (Château et al., 2019). Research in the United States shows that energy production could achieve 10% of requirements by covering 27% of appropriate water bodies according to Spencer et al. (2018).

2.6 Knowledge Gaps and Research Needs

Researchers must resolve multiple unanswered questions regarding FPV implementation. Long-term performance evaluations remain scarce because reliability studies require data spanning multiple years (Cagle et al., 2020). Environmental assessment of FPV systems remains underdeveloped, as studies focusing on comprehensive aquatic ecosystem effects remain scarce (Turney and Fthenakis, 2011). The investigation of social acceptance approaches remains insufficient even though these factors are significantly important for developing countries. A standardized framework for economic assessments remains incomplete due to insufficient analysis of land preservation and water conservation benefits (Mittal et al., 2017). These identified knowledge gaps are particularly relevant in the context of emerging markets like Sri Lanka, where specific geographical, environmental, and socioeconomic factors create unique implementation challenges. This research directly supports the study goals of establishing FPV feasibility, financial viability assessment, environmental and social impact evaluation and development of strategic implementation plans.

2.7 FPV in the Sri Lankan Context

2.7.1 Energy Landscape of Sri Lanka

Sri Lanka's renewable energy development began with hydropower development during the 1980-1990 Mahaweli Development Programme, but other renewable energy sources started advancing after 2000. Since new hydroelectric potential remains limited, alternative renewable energy sources have become vital for the country. The energy sector is Sri Lanka's largest source of greenhouse gas emissions, generating 62.7% of the country's total emissions, which amounted to 22.3 million tons of GHG emissions in 2021 (Emission Index, 2025). This significant contribution led to Sri Lanka's Nationally Determined Contribution (NDC) commitments to the United Nations Framework Convention on Climate Change (UNFCCC) in 2016 for 4-16% emission reductions, with updated commitments in 2021 targeting net zero carbon status by 2050. The Long-Term Generation Expansion Plan 2020-2039 (LTGEP) seeks to establish 3,425 MW of renewable energy capacity by 2039 including 1,323 MW of wind generation along with 2,210 MW of solar power and 144 MW of biomass power (CEB, 2019). This initiative will result in a 19% CO₂ reduction together with \$391 million in environmental cost savings.

2.7.2 Solar Potential and Current Implementation

Sri Lanka which lies within the equatorial belt shows considerable potential to use photovoltaic energy. Solar energy potential reaches 16 GW according to the Asian Development Bank from 2017 but it only generated 0.01% of the total energy in 2016 (Reuters, 2016) and increased to 434 MW by 2021 (IRENA, 2022). From 2016 to 2018 commercial PV plants established 51 MW capacity and rooftop installations reached around 170 MW (CEB, 2019).

2.7.3 Water Resources for FPV Deployment

Sri Lanka contains one of the most extensive reservoir systems in the world, comprising thousands of reservoirs spread throughout its territory. The country's water resources are sufficient for FPV deployment, with 103 natural river basins, in addition to more than 90 small coastal basins and 36 major

basins exceeding 256 km². Sri Lanka's irrigation and multipurpose reservoirs cover 1,699.41 km², with the most significant deployment potential found in large-scale and medium-scale perennial reservoirs. Large-scale perennial reservoirs account for 708.50 km² across 73 facilities, while medium-scale perennial reservoirs cover 170.01 km² across 160 facilities (Amarasinghe et al., 2002; Imbulana et al., 2006; WEPA), 2012). Most of the reservoirs in Sri Lanka have areas less than 1 km² but one reaches 60 km² and six reach 30 km² and forty measure 5 km² (Fernando, 2000). The dry zone landscape contains reservoirs that exist in defined watershed areas as part of specific cascades (Panabokke, 2001). Man-made reservoirs from the Mahaweli Development Programme offer promising FPV sites due to their size, infrastructure, and grid connectivity.

2.7.4 Challenges Specific to Sri Lanka

The implementation of FPV systems in Sri Lanka encounters specific geographical barriers which create implementation difficulties. The LTGEP 2020-2039 (CEB, 2019) identifies land scarcity as a reason for supporting water-based solar power but competing water demands demonstrate obstacles through the failed pre-feasibility study at Bandaragama village in 2018 because of irrigation concerns (Solheim, 2018). Wildlife encounters create special obstacles for Sri Lankan power infrastructure development. The swimming behavior of elephants in specific reservoirs threatens FPV installations by exposing them to both swimming-related damage including entanglement risks with mooring structures and damage that occurs when these animals access land during dry season water level decreases. Installation and maintenance personnel working in reservoirs containing crocodiles face safety hazards and panel performance may be affected by bird droppings which demand specific design modifications for local fauna. System integrity remains crucial during seasonal water level changes which occur because of monsoons and demands versatile anchoring systems to preserve panel orientation.

2.7.5 Early FPV Implementations in Sri Lanka

Sri Lanka has initiated its FPV implementation through projects at both small and utility-scale levels. The University of Jaffna operates a 46 kW system which performs energy generation and allows for research activities (see section 4.1.3 for more details). The 6.83 billion Korean Won funding from the Republic of Korea enabled the installation of two 1 MW pilot projects at Chandrika-Wewa and Kiriibban-Wewa reservoirs while the Korea Institute for Advancement of Technology served as the project monitor (Lanka News Web, 2023). Multiple major power projects are currently undergoing feasibility studies with Deduru Oya set to get a 100 MW facility and Ridigama gaining a 50 MW plant and Irakkaman receiving a 50 MW facility while Castlereigh will obtain a 34 MW plant through integration with its existing hydropower infrastructure (EconomyNext, 2025).

3. Methodology

The research uses an extensive methodology to understand both the opportunities and barriers that exist for implementing FPV energy systems in Sri Lanka. The research approach uses both qualitative and quantitative methods across four dimensions to study FPV system implementation in Sri Lanka while accounting for its specific geographical, environmental and socioeconomic characteristics.

3.1 Research Design

This analysis uses a mixed-methods research design which includes secondary data analysis and case study examination and comparative assessment. The research utilizes this combination of methods to determine Sri Lanka's specific implementation potential for FPV systems by examining international best practices. The research follows a systematic four-phase progression that begins with FPV potential assessment for resources and technical capabilities and continues to implementation challenge identification and barrier examination and ends with strategy evaluation for barrier mitigation before developing an implementation framework from synthesized findings.

3.2 Data Collection

3.2.1 Secondary Data Sources

This study draws its data from reliable secondary resources which include government reports from Ceylon Electricity Board, Sri Lanka Sustainable Energy Authority, together with World Bank and IRENA and ADB data as well as academic literature and technical documents and environmental measurements. The selection process for potential sites requires evaluation of four essential factors: reservoir capabilities, solar power availability, current energy systems, and social development metrics.

3.2.2 Case Study Selection

This research investigates Sri Lankan FPV installations through an examination of the 46 kW facility at University of Jaffna along with the 1 MW Chandrika-Wewa and Kiriibban-Wewa pilot projects and the pre-feasibility survey in Bandaragama village (2018). The research included these specific cases of FPV technology implementation because they met three fundamental requirements: (1) the projects demonstrated varying power capacities from 46 kW to 1 MW, (2) they spanned multiple regions across Sri Lanka and (3) they encompassed successful installations as well as facing substantial obstacles. The selection method provides strategic coverage regarding implementation obstacles and achievement elements that affect Sri Lankan conditions specifically. The research involved reviewing documents alongside performance data evaluations and international benchmark comparisons. Systematic comparison of findings from these case studies revealed success factors and implementation barriers while examining the influence of local conditions on outcomes. The research team utilized these findings to produce the implementation framework by integrating them with the results of dimensional analyses.

3.3 Analysis Framework

An integrated system analyzes FPV implementation using four linked dimensions which include technical aspects alongside economic aspects together with environmental aspects as well as social aspects. A comprehensive implementation strategy requires simultaneous consideration of four interrelated elements which should be treated as an integrated system rather than individual components. The analytical framework uses specialized methodological methods within each dimension without losing connection to other analytical dimensions.

3.3.1 Technical Feasibility Assessment

The assessment determines FPV implementation feasibility in Sri Lankan water bodies through analysis of solar resource potential and water body characteristics combined with grid connectivity and technical specification requirements.

3.3.2 Economic Analysis

The economic analysis uses cost-benefit methodology to study capital costs of floating structure construction with solar panels and anchoring systems and electrical infrastructure while also evaluating operational expenses for maintenance and personnel and insurance and revenue generation and indirect benefits.

3.3.3 Environmental Impact Assessment

The environmental impact assessment evaluates positive and negative effects through a matrix system that considers reduced water evaporation, land preservation, greenhouse gas emission reduction as potential benefits while assessing aquatic ecosystem effects, habitat modification, water quality changes as potential drawbacks and their possible mitigation strategies. The assessment rates impact significance on a scale from negligible to severe while assessing mitigation effectiveness across low to high measures. The assessment uses research-based guidelines for optimal coverage ratios to evaluate conservative (10-30%) coverage scenarios as per Mathijssen et al. (2020) and moderate (30-40%) coverage scenarios which align with Château et al. (2019).

3.3.4 Social Acceptability Analysis

Social acceptability receives analysis through stakeholder identification procedures and impact pathway analysis and acceptance barriers identification and engagement strategies development. The study shows how FPV deployment affects different stakeholder groups while identifying cultural economic and informational obstacles to acceptance specifically focusing on objections from fishing communities according to Château et al. (2019) and agricultural users per Solheim (2018).

3.3.5 SWOT Analysis Framework

A comprehensive SWOT (Strengths, Weaknesses, Opportunities, Threats) analysis framework evaluates internal and external factors affecting FPV deployment in Sri Lanka. The systemic classification of the factors (into internal capabilities (strengths and weaknesses) and external environment conditions (opportunities and threats)) is a systematic tool of the strategic assessment to be used to develop the implementation framework. The SWOT analysis is a compilation of results of the four dimensions of analysis to give strategic considerations in the development and deployment of policies.

3.4 Comparative Assessment

This research analyzes FPV deployment across multiple situations by assessing optimal practices together with technical variations and deployment strategies and integration procedures. The analysis benefits from this comparative perspective because it identifies adaptable solutions and recognizes the context-based restrictions that affect direct international application to Sri Lanka. The final methodology step merges findings from every dimension to create a potential assessment framework alongside a challenge reduction plan and implementation plan and policy recommendations.

3.5 Limitations

Lack of primary stakeholder interviews and expert surveys is the main methodological weakness whereby it was necessary to rely on the secondary sources to provide the stakeholder views and analysis of social acceptability. This approach is tolerant to various limitations that are based on the use of secondary data and uncertainty of economic forecasts and usefulness of primary field evaluation in environmental and social analysis. To minimize the limitations of the research, the triangulation of data is used as a strategy to compare the information in various sources which makes it reliable. Sensitivity analysis is applied to the economic projections to manage uncertainties and the study reports results of primary studies made in Sri Lanka. The methodological approach provides high potential of FPV implementation evaluation in Sri Lanka and establishes a foundation of fundamental strategic planning.

4. Results and Discussion

4.1 Potential for FPV Implementation in Sri Lanka

4.1.1 Resource Assessment

Large water resources within Sri Lanka provide facilities for FPV implementation. The 1,699.41 km² of perennial reservoirs in the country present the most suitable locations for FPV deployment according to Section 2.7.3. Sri Lanka stands as one of the countries globally with the most reservoirs per land area as reported by De Silva and Amarasinghe (2009) and FAO (1997) where the reservoir surface reaches 0.027 and 0.023 km² respectively for each 1 km² land area. The outstanding water facilities in this region create major opportunities for installing FPV systems. Renné et al. (2003) found that, solar power resource levels show substantial annual variations between 4.5 to 6.5 kWh/m²/day in Sri Lanka. During southwest monsoons the northeastern part of the country receives better solar resources than the southern and western regions which obtain their maximum resources during northeast monsoons. The maximum solar potential occurs between March and April just after the monsoon season ends (Renné et al., 2003). The implementation of such projects in Sri Lanka benefits from abundant water resources and favorable average global horizontal irradiation measurements ranging from 4.5 to 6.0 kWh/m²/day across most of the flat dry zone (ADB, 2012).

4.1.2 Technical Potential

Analysis of Sri Lanka's water resources reveals substantial FPV potential despite the country's limited land area of 65,610 km² (Weerakoon, 2017). Out of Sri Lanka's 1,699.41 km² of irrigation and multipurpose reservoirs (Imbulana et al., 2006), 708.50 km² consist of 73 large-scale perennial reservoirs and 170.01 km² consist of 160 medium-scale perennial reservoirs (Amarasinghe et al., 2002). Applying the 30% surface coverage threshold recommended by comprehensive global modeling as balancing technical feasibility and ecological impact (Jin et al., 2023) to just the large-scale perennial reservoirs yields 212.55 km² of potential deployment area. Given industry standards that 0.01 km² can accommodate 1 MW of FPV capacity (AFRY, 2023), these reservoirs could theoretically support 21,255 MW of FPV—more than triple Sri Lanka's 2025 power generation target of 6,900 MW (ITA, 2023). A key finding of this research is that quantitative analysis reveals that meeting this target would require only a fraction of the available reservoir area:

- Required area = $6,900 \text{ MW} \times 0.01 \text{ km}^2/\text{MW} = 69 \text{ km}^2$
- Percentage coverage = $69 \text{ km}^2 \div 708.50 \text{ km}^2 \times 100 = 9.74\%$

of large-scale perennial reservoirs.

The limited coverage requirement below 30% ecological threshold reveals that conservative large perennial reservoir development can make meaningful contributions to Sri Lanka's renewable energy sector. The study reveals crucial findings because Sri Lanka can reach its entire 2025 power generation target through FPV without creating substantial environmental damage to its water reservoirs.

4.1.3 Integration with Existing Infrastructure

Sri Lanka's hydroelectric facilities present significant potential for combining FPV and hydroelectric power generation. The Mahaweli Development Programme constructed major hydroelectric plants which encountered operational difficulties because of sedimentation and changing water supply conditions and competing water demands (Imbulana et al., 2006). The integration of FPV systems provides various advantages that combine favorable power output patterns with joint facilities and coordinated operational practices. The World Bank (2018b) reported that major hydropower facilities could achieve double their installed capacity by placing FPV systems on 3-4% of their reservoir area which would enable better water resource management through day-time solar generation. The combined operation of solar power plants with hydropower facilities enables the reduction of solar generation fluctuations and maximizes the potential of current transmission networks which proves especially beneficial for weak grid systems (World Bank, 2018b).

Technical viability of FPV implementation in Sri Lanka is proven by operating examples at the University of Jaffna and the pilot projects at Chandrika-Wewa and Kiriibban-Wewa. The initial installations deliver essential information about the system performance in local settings. The 46 kW installation at the University of Jaffna launched in January 2020 through a joint project of Western Norway University of Applied Sciences and University of Jaffna with support from Current Solar AS and the Royal Norwegian Embassy functions as a valuable demonstration project. The system contains a direct comparison element through its 2.5 kWp land-based reference system. According to a prototype model developed by the engineering faculty at the University of Jaffna (HRNCET, n.d.), FPV installations like this one can achieve a power gain of 4-5% compared to traditional ground-mounted systems. According to a similar study conducted at the Sabaragamuwa University, the additional power gain was 2.06% (Bandara et al., 2024).

The system incorporates HDPE pipes with glass fiber beams that have four anchoring points for managing Sri Lankan reservoirs' substantial seasonal water level changes which are characteristic of the country's monsoonal climate. The anchoring points serve as protective measures which stop the structure from touching the reservoir bed during dry periods while offering a tested technical solution for Sri Lankan conditions. Many stakeholders have visited the project including members from Sri Lanka Sustainable Energy Authority and representatives from the Ministry of Power and Energy and Ceylon Electricity Board as well as the Asian Development Bank. The Ceylon Electricity Board's Long

Term Generation Plan 2022-2041 mentions FPV as a technology that can 'resolve the land limitation issues for developing solar power plants' and recognizes its influence on national energy planning. The Sri Lanka Sustainable Energy Authority has documented various potential reservoir sites to establish large-scale FPV projects according to this document. The cost analysis reveals that setting up this project will require 9,500,000 Sri Lankan Rupees (LKR) with an expected payback period of 11 years. The document predicts that technological advancements and the large-scale deployment of power plants will reduce operational costs for this facility, further shortening the payback period. The research demonstrates financial progress trends for large-scale FPV facilities, aligning with international observations (University of Jaffna, 2022).

4.14 Strategic Assessment through SWOT Analysis

1.2 STRENGTHS (Internal Positive) Natural Resources: • 1,699 km² reservoirs (708 km² large-scale) • 4.5-6.0 kWh/m²/day solar irradiation • Equatorial location - consistent resources Technical Infrastructure: • Mahaweli hydroelectric facilities • Proven performance (Jaffna: 10-15% gain) • Existing transmission networks Policy Support: • 70% renewable target by 2030 • CEB Long-term Plan recognition • International partnerships (Korea, Norway) Performance Advantages: • Water cooling enhances efficiency • Reduced evaporation (70% reduction)	1.3 WEAKNESSES (Internal Negative) Technical Challenges: • Water level fluctuations (>10m seasonal) • Wildlife interference (elephants, crocodiles) • Monsoon/cyclone vulnerability • Limited local FPV expertise Economic Constraints: • 30% higher costs vs ground-mounted • Import dependency for components • Limited financing options • Uncertain revenue streams Regulatory Gaps: • No FPV-specific regulations • Fragmented institutional approach • Environmental compliance uncertainty
1.1 OPPORTUNITIES (External Positive) Market Trends: • Global FPV capacity doubling annually • Technology cost reductions • 65% hydro output increase potential Strategic Development: • Land scarcity solution (353 people/km²) • Climate finance opportunities • Regional leadership potential • Export market development Financing Opportunities: • International climate finance • Public-private partnerships • Community benefit programs • R&D partnerships with universities	1.4 THREATS (External Negative) Environmental Risks: • Aquatic ecosystem disruption • Climate change intensification • Protected area restrictions • Water quality concerns Social & Political Resistance: • Community opposition (Bandaragama) • Cultural sensitivities (ancient systems) • Livelihood concerns (fishing/agriculture) • Political/economic instability Market & Implementation Risks: • Competition from other renewables • Bureaucratic delays • International dependency

Figure 5: SWOT Analysis Matrix for FPV Implementation in Sri Lanka

The full SWOT analysis presents the strategic location of the FPV implementation in Sri Lanka through the systematic consideration of internal competencies as well as the external environmental influences. This evaluation combines the results of technical, economic, environmental and social analyses to determine some of the strategic factors that will play a determining role in the successful implementation. This SWOT analysis shows that Sri Lanka has considerable internal resources in water resources and solar potential, and considerable external opportunities in the growth of the global FPV market and climate finance. Nevertheless, the implementation process has to deal with major technical capacity gaps and regulatory systems vulnerabilities and overcome the risk of opposition by the community and environmental issues. This analysis directly provides the strategic insights that are used in the three-phase implementation framework, as shown in Section 4

4.2 Implementation Challenges

4.2.1 Technical Challenges

Field implementations and local conditions analysis reveal technical barriers that are particular to Sri Lanka's situation. Specific reservoirs of the country observe major water depth fluctuations which exceed 10 meters during seasonal transitions (Imbulana et al., 2006) along with cyclonic storms and monsoon rainfall that generates significant wind and wave patterns across reservoir surfaces. The operating requirements due to these conditions demand specific anchoring and mooring systems which must adjust to varying reservoir levels without damaging system components (Akole and Jadhav, 2018). The practical implementation of addressing water level variations in Sri Lanka's climate at the University of Jaffna FPV pilot site is provided under section 4.1.3.

Wildlife interactions produce particular challenges that exist exclusively in the reservoir settings of Sri Lanka. Wildlife research indicates that elephants in certain regions swim across reservoirs. This can potentially harm FPV structures both during swimming activities and during dry seasons when they reach shoreline areas. The problem stands out most critically in dry zone reservoirs since elephants regularly venture into aquatic areas. The selection of appropriate locations for site installations must happen based on documented elephant migration patterns and should focus on reinforcing entrance areas. Electric fencing surrounding the panel structures functions effectively to reduce damage from wild elephants especially when low water levels reveal the panels for walking. Long-term elephant movement data analysis will help identify the best placement of protective measures and seasonal management strategies but implementation requires this data collection to succeed. All solutions to prevent wildlife interactions with FPV systems must comply with wildlife conservation goals while receiving approval from the Department of Wildlife Conservation specifically for areas within or adjacent to protected zones. The occurrence of crocodiles in reservoirs leads to major safety hazards throughout installation phases together with maintenance operations. Sri Lankan reservoirs require rigorous safety measures together with personnel training to avoid possible impacts.

The design process should include assessment of bird-related interactions. The research conducted in Italy demonstrates that bird excrement causes significant immediate deterioration of FPV operational performance (Tina et al., 2023). According to their research it is advisable to position FPV modules on elevated terrain and at an angle above water levels to minimize bird contact. The protection capabilities of tracking systems that enable panels to reach higher angles through tracking periods remain under evaluation since they present potential weaknesses to strong wind conditions. Site operators must use specific active bird control methods when bird populations are substantial at specific locations.

4.2.2 Economic Challenges

The financial sustainability of FPV in Sri Lanka faces various challenges according to economic evaluations. The implementation of FPV systems leads to a 30% higher price than corresponding ground-based solutions (Ferrer-Gisbert et al., 2013). The main expenses stem from procuring imported floating platforms and specialty anchoring systems together with underwater cable installations. The scarcity of experience with FPV technology in local financial institutions drives financial institutions to see increased risk which leads to elevated financing costs. The existing renewable energy policies and energy tariffs lack explicit provisions for FPV systems which creates doubts about future income expectations (CEB, 2019). Studied through economic modeling it becomes evident that FPV systems will operate with financial stability when specific operational parameters are met in Sri Lanka. Using existing hydroelectric facilities to integrate FPV projects offers the best economic outlook since they can recover investments in 8 to 10 years while generating internal returns above 12% through a 25-year operational period (Ranjbaran et al., 2019).

4.2.3 Environmental Considerations

Environmental assessments help identify areas where negative impacts will occur together with potential methods of impact reduction. Areas covered by FPV installations receive reduced sunlight which impedes photosynthesis and the production of primary matter in ocean environments. Research shows that the installation of FPV systems should prevent exceeding 30-40% coverage in all bodies of water to best protect natural ecosystems (Château et al., 2019). The shading elements of FPV systems reduce water loss by evaporation while blocking sunlight for algae but materials in the components may erode into the water. A large number of Sri Lankan water reservoirs nurture multiple ecosystems which host endemic species as well as serve as habitats for migratory birds. Tests conducted on current facilities through environmental assessment show that when properly situated and designed FPV systems produce satisfactory environmental results.

4.2.4 Social Acceptance Barriers

Research into stakeholder behaviors combined with actual examples demonstrate that Sri Lanka faces multiple obstacles to accept FPV implementations in society. The Bandaragama incident of 2018 demonstrates fundamental proof of social acceptance concerns. A Norwegian private solar company launched the FPV concept in Sri Lanka during 2017. As part of their assessment the company investigated the possibility of installing a 50-kW FPV pilot plant in Bandaragama in western province of Sri Lanka during 2018. A 50-kW pilot project initiated by a Norwegian solar company failed after the community vetoed it through local discussions about the project. The local authorities presented their formal opposition to FPV technology based on the identified impacts on biodiversity and community along with local sources of income. The private sector stakeholder interviewed in May 2021 explained that local farmers lacked the broader understanding of renewable energy versus local power plants while local authorities failed to identify any benefits from the project. The people who grew paddy and banana and vegetables in this tank area felt threatened because Sri Lankans consider farming and land and water to be three vital elements which must receive proper attention according to Solheim (2018). The project stopped due to the relational materiality element which demonstrated that FPV technologies face challenges when introducing them to populations whose lifestyles depend on water for farming.

The Sri Lankan storage facilities serve as vital sources for irrigation, drinking water distribution, fishery services and flood protection. However, dependent communities express concerns over water availability and quality due to competing demands for these resources. The structure of commercial and subsistence fishing remains crucial to local livelihoods, as their economic value outweighs projected losses from energy projects (Château et al., 2019). The aspect of historical significance creates additional obstacles for project development. The water-collection systems in Sri Lanka stand as one of the oldest water-management systems in worldwide history which originated in the 4th century BCE (Abeywardana et al., 2018). The historical systems developed practical water management structures alongside areas with cultural worth. The regulations protecting archaeological sites through legislation can restrict building activities which might limit available implementation methods. Recreational use presents additional concerns. The installation of FPV systems generates negative impacts on both tourism operations and water recreational activities near reservoir areas that hold visual appeal for their scenic beauty. Technical and economic feasibility serve as inadequate factors for delivering successful implementation results.

4.3 Mitigation Strategies

4.3.1 Technical Solutions

Multiple technical solutions exist to tackle the identified challenges by referring to existing implementations and global best practices. Adjusted cable systems and tension systems in flexible mooring designs enable stability maintenance during water level changes (Ferrer-Gisbert et al., 2013). The implementation of reinforced structures at both access points and shorelines helps decrease wildlife damage especially from elephant activity. Performance monitoring and impact assessment results can

drive design modifications because large implementations split into smaller phased modules. The implementation of advanced forecasting technologies coupled with control systems and battery storage integration potential enables solutions to grid stability issues (Cazzaniga et al., 2019).

4.3.2 Economic Incentives and Business Models

Multiple strategies exist to boost the financial sustainability of projects. Specific feed-in tariffs established for FPV technology which account for its additional benefits as well as costs compared to traditional solar installations will enhance financial performance and draw investment. The partnership between public institutions and private builders enables shared risk management and infrastructure utilization to decrease the total installation expenses (Gamarra and Ronk, 2019). The economic evaluation method which considers water conservation and land conservation and grid benefits demonstrates better financial prospects than standard energy-only assessments.

The economic information from Sri Lanka's first FPV pilot at the University of Jaffna shows promising financial results while expecting a 11-year payback period which could shorten further for bigger implementations because of economies of scale (see section 4.1.3 for details).

4.3.3 Environmental Management Framework

A complete management system has been designed to handle environmental aspects. The tiered siting process selects hydroelectric and irrigation reservoirs before natural lakes for development but classification systems determine design requirements based on water body types. Semi-transparent panels and proper spacing between panels enable some light transmission which minimizes ecological damage (Sujay et al., 2017). Water quality monitoring throughout the installation process allows researchers to collect data which helps identify operational changes for impact mitigation. Dissolved oxygen levels as well as temperature stratification and turbidity information should be tracked through complete water quality monitoring systems. Management responses will activate when negative environmental impacts reach pre-established thresholds of key parameters.

Future development of FPV technology should include compatibility with emerging solutions in water quality management. The study conducted by Mikaeili et al. (2025) demonstrates the development of Cu-doped TiO₂ nanofibrous structures combined with real-time visible light-responsive self-supported nanocatalyst-based photocatalytic sensors for future FPV deployments to resolve water quality problems that could emerge from substantial installations.

4.3.4 Community Engagement and Benefit Sharing

A solution to social acceptance barriers demands complete engagement approaches. The process of consulting communities should begin at the planning stage to integrate their insights and concerns directly into project development. When people receive straightforward accessible information about project effects and mitigation steps their trust grows and misunderstandings that drive resistance diminish. A program which distributes tangible benefits from FPV implementations to local communities will enhance their acceptance of these projects. World Bank (2018a) reports that projects which include full benefit-sharing systems succeed in obtaining high community acceptance levels even when opposition was first detected.

A different set of planning strategies must be established to resolve recreational needs together with aesthetic considerations. Developing strategic zoning plans alongside partial coverage strategies protects water-based activity areas while reserving particular sections for energy production. Primarily based on visual impact assessments performed ahead of time the placement of PV facilities can be identified to minimize their impact on aesthetics from typical viewing locations. Renewable energy centers can become educational destinations for the public by adding viewing platforms together with displays that explain renewable energy principles thus creating new recreational options and public understanding of clean energy.

4.4 Implementation Framework

The analysis of potential along with challenges and mitigation strategies supports a three-stage implementation framework for FPV in Sri Lanka. This proposed framework stems from research findings because Sri Lanka does not have an existing government-made framework to deploy FPV. The three-phase implementation framework is based on the strategic analysis of the detailed SWOT analysis (Section 3.3.5), which presents the main internal capabilities and external factors that affect the successful implementation of FPV. Phase 1 establishes foundational components by developing policies and technical standards while building capacities and expanding pilot projects during a period of 1 to 2 years. Phase 2 (strategic scaling, 3-5 years) targets commercial implementation of hydroelectric integration combined with regional expansion and technology localization while performing performance tracking. Phase 3 (Mainstream Deployment, 5+ years) makes FPV ready for mainstream renewable energy adoption through competitive procurement of advanced applications and export development alongside comprehensive integration.

The sequential implementation process enables knowledge acquisition alongside adaptation and controlled growth which establishes fundamental technical and economic infrastructure and regulatory structures and social readiness for ultimate success.

The framework shows the step-by-step process of building the foundation, scaling strategically and deploying to the mainstream, with cross-cutting considerations that cut across all layers. The phases have certain activities, schedules, and deliverables, and key success factors guarantee successful implementation in the whole structure.

The country of Sri Lanka has launched initial components from this framework. The Cabinet of Ministers through the Ceylon Electricity Board has received authorization to select investors for FPV projects at Randenigala and Moragahakanda and Kalawewa reservoirs through complete feasibility studies while adopting transparent competitive procurement methods (Daily FT, 2024). The 100 MW Samanalawewa Reservoir FPV Park in Sabaragamuwa represents the shift toward commercial deployment as construction will start in 2026 and commercial operations are scheduled for 2028 (Power Technology, 2024). The financial support for infrastructure development in FPV deployment comes

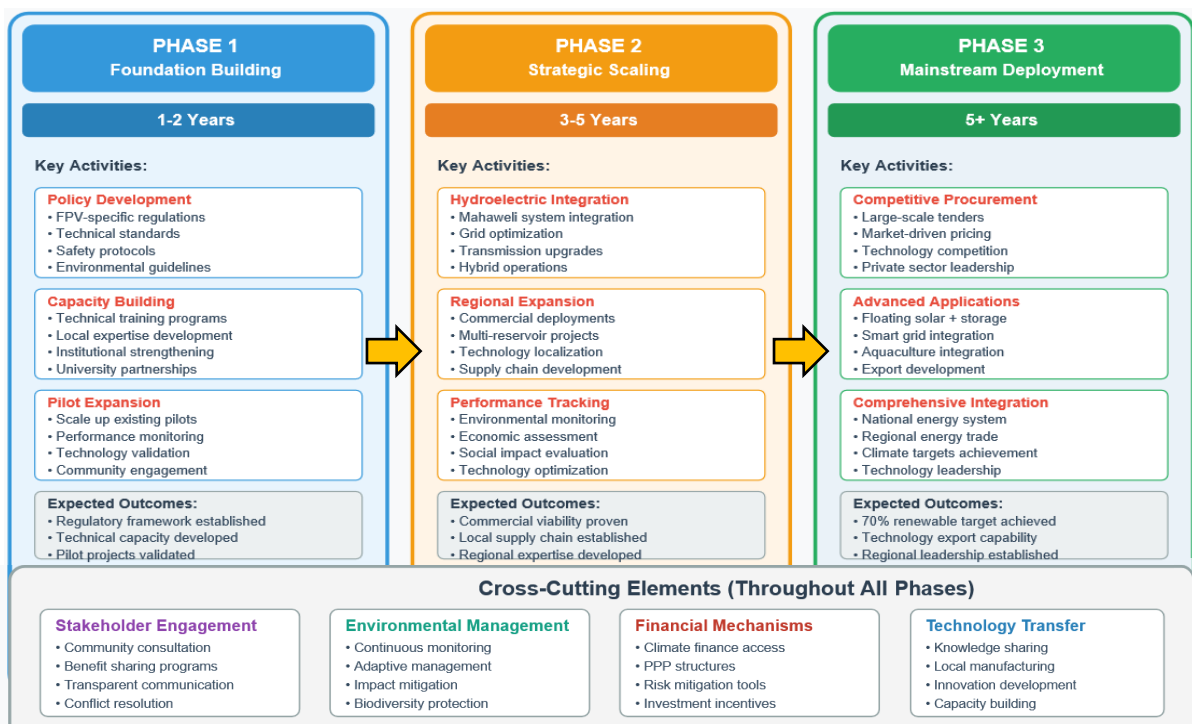


Figure 6: Three Phases FPV Implementation Framework for Sri Lanka

from a 23.4 billion rupees budget from the Ministry of Irrigation which includes 6.9 million rupees specifically for reservoir maintenance (Xinhua, 2024).

4.5 Implications for Policy and Practice

It is bound by secondary sources of data and thus it has less information regarding the local stakeholder views especially the fishing and agricultural communities. The case of Bandaragama shows that community approval is crucial, but that close stakeholder involvement is required to obtain comprehensive implementation obstacles and solutions.

Future Research Priorities:

- Semi-structured interviews of fishing populations, farming users and state organizations
- Survey questionnaire addressing the technical experts and policymakers
- Existing FPV sites Environmental monitoring studies
- Specific economic analysis that takes into consideration land and water conservation benefits

Such constraints imply that the first phase of the implementation framework must be stakeholder-wide consultations.

The research results create multiple important consequences which affect policymakers in addition to developers and community members. Implementing FPV systems demands harmonized policies from multiple government sectors including energy sector along with water resources sector and environmental sector and sector of rural development.

Specific policy recommendations include:

1. The development of special FPV regulatory guidelines will determine technical specifications and safety protocols and environmental protocols for water-powered solar technologies.
2. A strategic electricity payment method should exist to respect FPV's particular operational strengths and financial requirements relative to standard solar systems by following separate rate guidelines.
3. The establishment of renewable energy targets aimed at FPV technology should constitute a specific percentage allocation to guarantee market certainty.
4. New financial instruments should be established to support FPV deployment by offering low-interest loans and long-term repayment terms as well as partial risk protection mechanisms.
5. The guidelines must include mandatory initial meetings between developers and users of water resources who operate in fishing and agriculture.
6. Local communities should benefit substantially from FPV installations through the execution of benefit-sharing programs.
7. Programs for capacity building should be encouraged to foster competent staff at every stage of FPV value chain installation and upkeep.

The nation of Sri Lanka can benefit from FPV as it allows progress in renewable energy objectives and helps overcome environmental limitations that affect traditional solar installations. Sri Lanka has natural benefits for swift FPV adoption since most of its reservoirs belong to hydroelectric facilities. The implementation of FPV through technical, economic and environmental alongside social assessment can create a substantial effect on Sri Lanka's sustainable energy outlook that other developing nations facing similar constraints might adopt.

5. Conclusion

The research examines the FPV implementation potential in Sri Lanka by conducting investigations on required technology aspects alongside economic assessments and ecological evaluations and social implications. The presented data shows strong deployment prospects for FPV systems although key obstacles need careful management through systematic planning methods.

Implementation and operation of the University of Jaffna FPV pilot established an influence on national energy policy by gaining recognition of this technology from the Ceylon Electricity Board in its Long Term Generation Plan 2022-2041. The 46 kW system performed essential demonstration duties hosting performance data from Sri Lankan conditions which introduced technical manifestations to policymakers and utilities and private developers.

The nation of Sri Lanka maintains perfect conditions for implementing FPV because it has significant water resources and agreeable solar irradiance levels. The power generation of 6,900 MW could be achieved by harnessing 9.74% of the large-scale perennial reservoir surface area which amounts to 69 km² and this would fulfill Sri Lanka's entire 2025 power generation goal without causing significant environmental damage. The productive integration of FPV with the Mahaweli hydroelectric system shows promise because it allows usage of current transmission lines for dynamic power generation.

To achieve successful large-scale implementation several important challenges need additional attention. Large-scale deployment faces technical barriers from managing substantial water level variations and building for adverse weather conditions and handling wildlife encounters especially elephant interactions and maintaining power system stability because of additional intermittent power generation. The high capital expenditure requirement of floating systems presents an economic obstacle compared to ground installations while financial limitations stem from unfamiliarity of technological solutions as well as unclear policies for incentive and tariff structures (Ferrer-Gisbert et al., 2013). The proper management of environmental aspects must focus on the impacts of shading effects and water quality transformations in aquatic ecosystems (Château et al., 2019). The main obstacle to solar energy acceptance came from social approval because the community in Bandaragama village rejected the prefeasibility study due to their concerns about irrigation system changes and fishing viability despite technical proof (Solheim, 2018).

Multiple essential methods appear in the research to handle these problems. Multiple technical solutions such as adaptive anchoring systems coupled with reinforced structural designs and modular deployment methods and smart grid integration will address physical and operational constraints. Financial viability of FPV systems improves through dedicated tariffs and public-private partnerships combined with benefit combination evaluation followed by controlled expansion strategies. The ecological impact of FPV systems can be lessened by implementing a tiered siting process together with modified design elements for light penetration as well as continuous monitoring systems and adaptive management systems. A social approach to project success requires stakeholders to engage early and transparent impact communication alongside benefit-sharing schemes and livelihood inclusion to generate community acceptance as noted in World Bank (2018a).

In order to achieve mainstream deployment, competitive procurement, advanced applications, export potential development, and comprehensive integration, a three-phase implementation framework is suggested. The first phase is foundation building, which includes policy development, technical standards, capacity building, and pilot expansion (1-2 years). The next phase is strategic scaling, which prioritizes hydroelectric integration, regional diversification, technology localization, and performance monitoring (3-5 years).

This study expands the still scarce information about developing FPV systems in densely populated areas that contain substantial water resources in developing nations. Integrated approaches succeed better than sequential methods because they show the necessary importance of addressing technical economic environmental and social factors at the same time. The examination shows that FPV brings major advantages to Sri Lanka's power consumption but its successful use depends on detailed analysis of area-specific conditions and citizen needs along with environmental protection considerations. The strategic evaluation based on SWOT analysis affirms that Sri Lanka has the required internal resources and external opportunities to implement effective FPV successfully as long as technical capacity shortages and social acceptance difficulties will be addressed systematically in a three-phase implementation plan.

Future research should focus on several key areas specifically relevant to Sri Lanka's context:

1. Priority area: Long-term performance and degradation assessment of FPV systems in tropical monsoonal conditions, particularly examining resilience during cyclonic events;
2. Comprehensive environmental monitoring methodologies adapted to Sri Lanka's aquatic ecosystems to establish site-specific impact thresholds and optimal coverage ratios;
3. Critical need: Stakeholder interviews and surveys of the community to gather primary data to come up with culturally sensitive models of engagement that take into account the particular issues of the fishing, agricultural and indigenous populations in various parts of the country;
4. Technical innovations for improved wildlife compatibility, especially regarding elephant and crocodile interactions with FPV infrastructure.

FPV delivers strong potential to expand Sri Lanka's renewable power generation capabilities alongside optimal utilization of land resources as well as strengthening the power network through water management features. This research proposes a three-phase framework that can make FPV contribute significantly towards sustainable energy development in Sri Lanka while demonstrating how other developing countries with limited land availability and energy issues can proceed.

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ICSD 163

CIRCULAR ECONOMY FOR RESILIENT DISASTER RECOVERY: STRATEGIES FOR SUSTAINABLE REBUILDING AND COMMUNITY EMPOWERMENT

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Abstract: Natural and anthropogenic disasters have wide implications on the environment as well as the society including severe resource wastage, environmental degradation and ensuing long-term socio-economic problems. In contrast to linear approaches, traditional disaster recovery models are often introduced upon and seek temporary solutions that are rarely sustainable or resilient, increasing vulnerability of communities to future risks. This work examines how linking the principles of circular economy into disaster recovery can enable sustainable and resource intensive recovery approaches. A comprehensive review of 30 peer-reviewed papers published between 2014 and 2024 was conducted using ScienceDirect, and Google Scholar, to evaluate the sustainable benefits of integrating a circular economy in the disaster recovery process. Articles were selected based on English-based open-access availability, full-text accessibility, and robust citations, while duplicate entries were excluded from the review. The review highlights three key strategies which are incorporating recycled construction materials, promoting modular and adaptive design in rebuilding infrastructure, and leveraging local resource recovery systems to minimize waste. The collective of these strategies brings into focus on resource efficiency, material recovery, and sustainable infrastructure development, and which taking into account environmental and economic constraints. Adopting circular economy principles into disaster recovery increases the life cycle planning, supports outbound nature-based solutions, and cuts waste generation by a great margin. Additionally, active collaboration amongst stakeholders (government agencies, private sectors, and local communities) is vital for realization of the principles propounded here. Stakeholder collaboration in addition, improves community resilience, and deals with socioeconomic inequalities in vulnerable environments. This paper presents the integration of circular economy principles into different phases of disaster recovery, and illustrates how this approach empowers communities, enhances living standards, and achieves sustainable outcomes. In addition to reducing the short term environmental and social effects of disasters, these approaches lay the groundwork for promoting long term sustainability and resilience in post disaster contexts.

Keywords: Adaptive Design; Circular economy; Disaster recovery; Life cycle planning; Modular construction; Waste minimization

1. Introduction

Data from the United Nations indicates that the 2050 global population will reach 9.6 billion thus creating stronger requirements for disaster impact sustainability solutions (Falcon et al., 2022). The combination of natural occurrences and human-caused events generates major resource depletion along with environmental damage that leads to long-running effects on social economy. The existing Disaster Recovery Models (DRM) function mainly in a linear fashion and provide temporary solutions that make systems more vulnerable to disaster recurrence (Ali et al., 2023; Montalvo-Falcón et al., 2023).

Disaster management fully embraces Building Back Better (BBB) as its central principle because it requires recovery actions beyond restoration to enhance pre-disaster standards while establishing stronger resilience (Kennedy et al., 2019). In BBB initiatives exist proactive points that require business owners to integrate sustainability principles into their recovery processes which strengthens community resilience when they face future disasters.

The circular economy (CE) brings a revolutionary method to handle disaster recoveries. CE remains a suitable answer to cope with these difficulties because its three core principles center on efficient resource usage alongside habitat regeneration and materials recycling (Väänänen, 2024). CE methods which convert waste resources into valuable materials can help close essential gaps in regular disaster recovery practices because they handle large debris volumes efficiently (Fetter & Rakes, 2010). Adding CE principles to BBB systems results in more enduring rebuilding solutions which builds disaster-affected community resilience over the long term. (Karimi et al., 2023; Pradhananga & ElZomor, 2023). Certain significant connections exist between the principles of BBB and CE. The frameworks show dedicated attention to sustainability but follow different approaches to achieve this goal. The implementation of BBB addresses infrastructure concerns and community needs while CE depends on how organizations handle material lifecycles and reduce waste numbers (Kennedy et al., 2019). The implementation of CE principles after disasters brings multiple advantages that reduce resource waste and help utilize local workers and items (Antonioli et al., 2022). The application of consultations under CE helps reduce social and economic vulnerabilities that disasters typically exacerbate since this method promotes community-driven disaster reconstruction plans ((Jacobs et al., 2022).

The vast benefits of community engagement do not currently match up with current structures in disaster recovery frameworks. The available literature about CE in BBB efforts remains scarce and researchers have not found effective ways to unite these approaches for better disaster recovery results (Kennedy et al., 2019). Research demands both a structured analysis of current knowledge about using CE in disaster recovery together with an evaluation of essential elements and potential difficulties for implementing CE within Building Back Better programs. The main purpose of this study includes reviewing CE usage in disaster recovery practices as well as studying factors facilitating and restraining CE in BBB initiatives. This research seeks to accomplish these objectives which will contribute to the current lack of knowledge about CE support for disaster recovery and community resiliency development. The research presents an applied strategy for disaster recovery paradigms that enables policymakers together with practitioners to develop better disaster reconstruction methods.

The paper establishes theoretical-practical bridging for CE principles to show how disaster recovery programs can evolve through CE principles and generate sustainable community outcomes. The research concludes by recommending new approaches to climate change and population increase requirements to policymakers and practitioners and scholars.

2. Methodology

The systematic review (Ali et al., 2023) research approach was selected for assessing CE applications in disaster management to lower research bias and boost study quality. The research used ScienceDirect and Google Scholar databases for extensive literature identification of peer-reviewed papers from 2014 to 2024. The search required specific terms including ‘circular economy’ AND ‘disaster recovery’, ‘sustainable reconstruction’ AND ‘waste management’ and ‘resilience’ AND ‘resource recovery

systems’ as well as ‘adaptive design’ AND ‘rebuilding infrastructure’. Boolean operators such as the AND and OR function were employed within the research parameters to build a wide base of studies investigating the connection of CE principles to disaster recovery. Selection of studies followed research objectives through evaluation of their full-text access creating an assessment of how high their citation indexes were.

The research kept its credibility high by strictly applying both inclusion and exclusion criteria. Articles were included in the study based on their publication in peer-reviewed journals and English authorship while also focusing on CE principles in disaster recovery phases of disasters with theoretical frameworks and quantitative data or case studies supported by sound references. All articles that passed through the inclusion and exclusion criteria were accepted for further review. The research included articles from peer-reviewed journals and excluded conference abstracts, reports and duplicate entries from different databases and publications which failed to address disaster recovery or CE principles. The selected studies amounted to 30 which underwent a standardized data extraction process that systematically recorded important information about each study. The analysis included information about study objectives along with methods and CE approaches discussed together with research findings regarding sustainable recovery and suggestions for future investigation. The organized method enabled researchers to compare and combine data findings across several studies.

Thematic analysis as described by Oberholzer and Sachs (2023) allows the study to identify recurring patterns as well as ongoing trends and dominant themes in the reviewed literature. The analysis focused on CE rebuilding methods which emphasized the redirection of building materials and adaptable structure design and local materials collection systems. This study evaluated how CE-based methods affect environmental and economic and social impacts and clarified government and private sector and community relationships for developing sustainable partnerships.

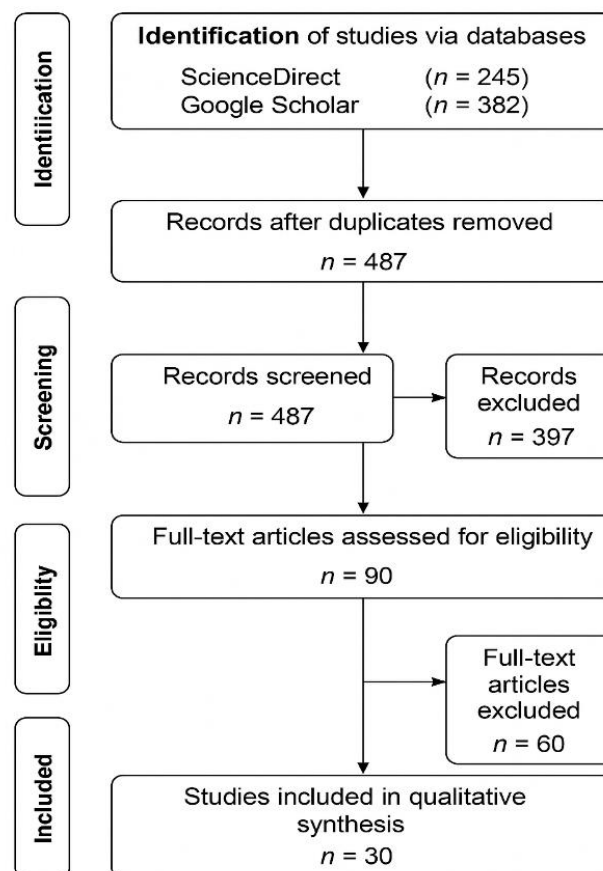


Figure 1: Framework of methodology

The researchers performed quality assessment on selected studies based on standardized appraisal tools as described by Ali et al. (2023). The assessment process evaluated studies by their research methodology while assessing their connections to research objectives and analyzing both the data analysis quality along with drawn conclusions. The methodical quality evaluation system was instrumental for selecting studies that maintained quality standards to support the systematic review. The systematic review methodology delivers a responsible and extensive evaluation concerning circular economy implementations to boost sustainable disaster recovery efforts. The investigated research delivers findings that will benefit policymakers and practitioners together with researchers who want to enhance resource usage and recovery in disaster zones.

3. Results and Discussion

A systematic review of literature about Circular Economy principles in disaster recovery creates the foundation of this section. The analyzed research papers present crucial guidelines that enable efficient resource-efficient recovery processes with amplified resistance. A detailed analysis of findings exists across three main sections and includes advantage and disadvantage evaluations while discussing the future potential of CE during disaster recovery efforts.

3.1 Integration of Circular Economy Principles in Disaster Recovery

The systematic review analyzed three main strategies which enable disaster recovery processes to incorporate CE principles beyond conventional linear recovery methods. Three main strategies dominated the 30 evaluated studies.

3.1.1 Recycled Construction Materials

The waste stream contains Construction and Demolition Waste (CDW) as its most significant component during circular economy operations and disaster reconstruction projects. The study focuses on creating a method to manage CDW during reconstruction tasks while reducing environmental damage and maximizing resource efficiency. The building process following emergencies needs immediate construction while conventional supply networks might be disrupted thus this methodology becomes essential. After calamities the recovery of debris materials supplies essential building materials while it decreases environmental strain caused by resource extraction and disposal operations. Scientific studies indicate that crushed concrete and bricks can be successful as sustainable building materials for construction purposes (Wang & Guo, 2022; Xu et al., 2021).

The use of recycled construction materials represents a vital factor for developing sustainable and resistant reconstruction practices. The utilization of such materials supports both resource-efficient operation and environmental monitoring as well as economic reconstruction affordability. Digital tools together with overcoming regulatory and technological barriers enable communities to enhance these recovery approaches making them economically sustainable also environmentally friendly.

3.1.2 Modular and Adaptive Infrastructure Design

At present disaster recovery depends on the CE system's combination of modular and adaptive infrastructure systems to establish quick sustainable housing solutions that are resilient in nature. Standardized elements in modular housing enable swift and efficient assembly or disassembly processes especially in disaster areas according to the prefabrication principle (Mackenbach et al., 2020). Modular shelters have adaptable dimensions that enable facilities to adjust their size according to demand needs improving resource allocation. The modularity of houses becomes environmentally friendly and affordable when they are combined with circular economy principles which produce both minimal material waste and extensive reuse potential (Karimi et al., 2023). The recovery process becomes sustainable through this method which also conserves scarce resources.

Modular houses can be integrated with adaptive infrastructure strategies which enable brief transition stages according to the changing needs of communities. The implementation of this flexibility streamlines reconstruction efforts while lowering rebuilding expenditures thus improving overall

vulnerability of struck areas (Çetin & Kirchherr, 2025; Moreno-Sierra et al., 2020). Following CE principles through adaptive infrastructure integration together with modular design enables the delivery of disaster response housing solutions that support flexible development needs of the long-term.

3.1.3 Local Resource Recovery Systems

The implementation of CE in disaster recovery requires local resource recovery systems that seek to recover used materials for sustainability and resilience objectives. When product materials are designed for disassembly it becomes a circular method of reusability after reaching their original purpose according to Van Hullebusch et al. (2021). The recovery process in Central Italy revealed that both social connectivity and new development opportunities emerged after earthquakes (Arnetoli & Bologna, 2022). Also according to Arnetoli & Bologna (2022) CE methodology transformations in the demolition and construction sector help handle refuse and maximize material reuse potential. Using Nature-based solutions (NBS) leads to better solid and liquid waste quality and helps develop urban agriculture and bolsters local resilience (Van Hullebusch et al., 2021).

The practice of producing energy or creating compost from local biowaste enables a CE cycle while reducing dependency on outside materials and resources according to Mackenbach et al. (2020) and Xu et al. (2021). Self-sustainable recovery together with reduced logistics challenges and boosted economic development can result from implementing local resource recovery systems despite the systematic and infrastructure complexity barriers (Pinyol Alberich & Hartley, 2024). The developed comprehensive framework combines dominant circular economy principles into disaster recovery phases.

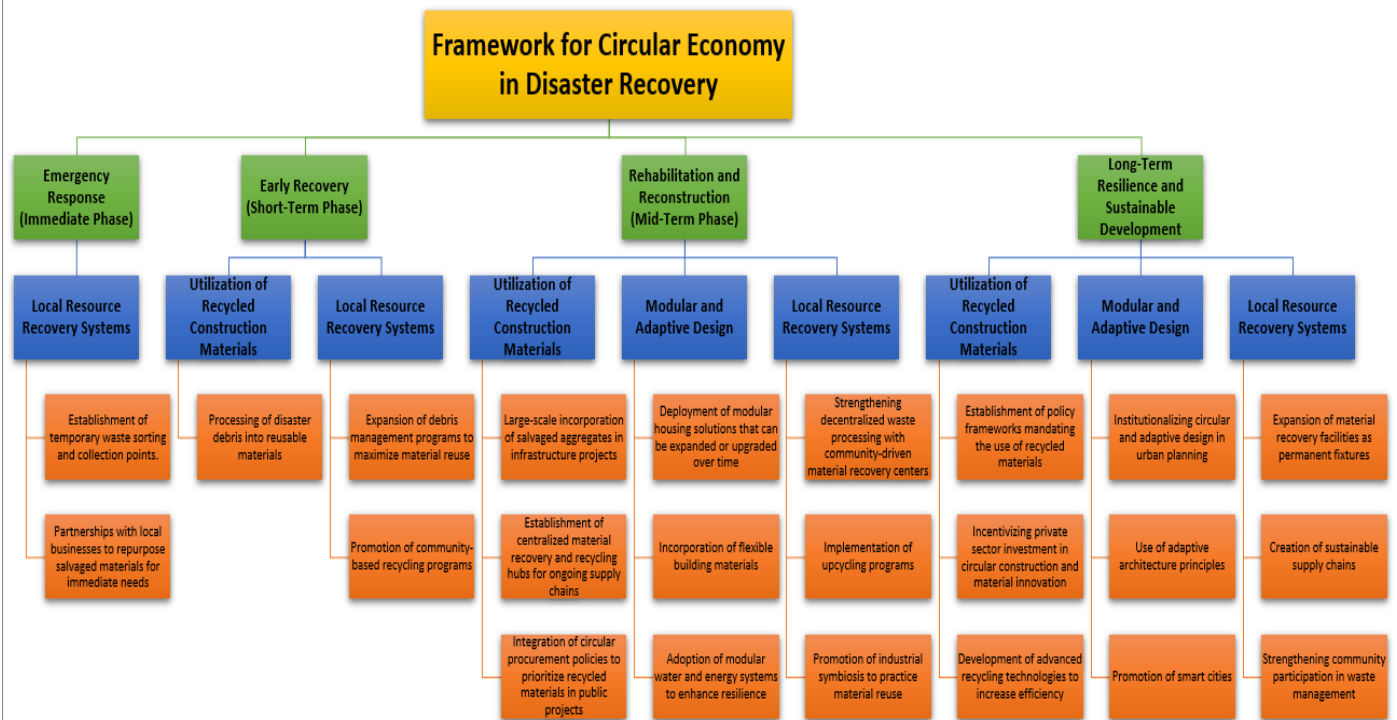


Figure 2: Framework for Circular economy in Disaster Recovery

3.2 Benefits of Circular Economy in Disaster Recovery

The implementation of Circular Economy principles during disaster recovery brings substantial advantages throughout social, economic and environmental spheres.

3.2.1 Environmental Benefits

The implementation of CE principles helps disaster management access its resources better while lowering unnecessary material waste. CE decreases power requirements as well as landfills along with GHG emissions yet supports environmentally friendly reconstruction projects (Pineda-Martos et al., 2024). The Ellen MacArthur Foundation (2015) explains how material recycling and reuse help lower environmental pressure by decreasing the need for extracting and transporting original substances. The reconstruction process needs materials to be reused twice to maximize effectiveness. Sustainable reconstruction can be promoted through the temporary structures built for demounting while maintaining material recovery cycles leading to less landfill waste (Arnetoli & Bologna, 2022).

Nature-based solutions (NBS) strengthen urban resilience through enhanced infrastructure integrity and serving as part of the ecosystem. Urban area functioning after disasters improves through solutions that counter urban heat effects together with stormwater management capabilities (Pineda-Martos et al., 2024). CE practices enable environmental gains through sustainable practices because community members actively participate in such practices. Japanese fishing communities experienced increased environmental protection after post-disaster adaptations which resulted in multiple social and monetary advantages together with enhanced conservations of marine resources (Uchiyama & Kohsaka, 2018). The circular economy delivers multiple environmental advantages to society yet battles with community participation and equal treatment. Stakeholder management plays a vital role for businesses to strike the correct equilibrium between multiple factors which support maximum implementation of CE principles in disaster recovery.

3.2.2 Social Benefits

The implementation of circular economy methodologies allows communities to sustain their resources independently using limited external backing (Ma et al., 2021). The local training of personnel to achieve sustainable construction platforms and waste recycling and resource recovery reduces external dependencies crucial for building future sustainable communities (Allimadi et al., 2021; Karimi et al., 2023). Japanese fishermen adapted their practices post-disaster to boost resident involvement along with disaster readiness according to Uchiyama & Kohsaka (2018). At the same time circular housing programs enhance social capital through tenant group interactions. Publicly saved money from circular policies gets redistributed to poor neighborhoods thus creating social inclusivity (Karman et al., 2024). Restoring community involvement during recovery periods helps generate social agreements that work toward sustainability goals.

The implementation of CE strategies creates dual advantages between environmental conservation and economic advancement by increasing public resource effectiveness and supporting economic growth strategies in the specific area (Moreno-Sierra et al., 2020; Van Hullebusch et al., 2021). Sustainable practices improve environmental quality and human well-being to create better unity among people (Van Hullebusch et al., 2021). The implementation expenses along with community backing require additional efforts to address the constraints in front of achieving more participation.

2.3. Economic Benefits

The circular economy presents great opportunity in disaster recovery since it promotes both resource efficiency and waste minimization to bring economic advantages. Recycled materials from deconstruction and reuse activities together with modern recycling methods reduce costs and create new markets and waste reduction (Aiguobarueghian et al., 2024; Pradhananga & ElZomor, 2023). The implementation of circular strategies produces innovative solutions together with new job opportunities which remain fundamental after disasters as well as for sustainable development (Aiguobarueghian et al., 2024; Tabaev et al., 2024). ^{٧٠}HOLDER (Hartley et al., 2024) suggests that communities become

prepared for future disputes by establishing reliable supply chains together with local market creation. The Japanese marine circular economy approach uses local recovery measures to both maintain and reconstruct existing systems according to Uchiyama & Kohsaka (2018). Some factors including policy support and market barriers exist yet they cannot prevent circular economy practice success from generating maximum economic sustainability with reduced long-term costs (Pinyol Alberich & Hartley, 2024; Wang & Guo, 2022).

3.3 Challenges and Opportunities in Circular Economy Integration

The availability of potential advantages from CE for disaster recovery gets obstructed by several implementation hurdles. The implementation of CE for disaster recovery faces three main hurdles regarding standardization guidelines and insufficient collaboration between stakeholders and the conversion process from traditional models to circular systems.

3.3.1 Challenges

The implementation challenges of circular economy integration within disaster recovery plans exist due to distinct disaster response requirements which require unique solutions designs. The lack of pre-disaster mitigation strategies particularly post-use management of temporary structures limits optimal resource management and optimization according to Pradhananga and ElZomor (2023). The socio-ecological urban system does not operate according to a well-planned circular model while simultaneously remaining very vulnerable to risks throughout the recovery process (Arnetoli & Bologna, 2022). Organizations face two main problems when collecting recycled materials because of many diverse materials sources combined with volatile market conditions affecting recycling operations (Jacobs et al., 2022). Stakeholder engagement becomes difficult mainly because it is challenging to synchronize interests between different groups including both local communities and policymakers (Hartley et al., 2024). Different regions adopt various approaches to circular economy management in disaster recovery because implementing this practice requires extensive transformation of mindsets and resources and technologies to move beyond linear models (Karimi et al., 2023). These concepts usher new strategies and sustainable city growth mechanisms for future developments.

3.3.2. Opportunities

The implementation of circular economy principles offers great potential for building disaster recovery approaches that combine sustainability with resilience. The construction of reusable temporary housing and implementation of ecologically-based stormwater and heat reductions extend infrastructure life duration while minimizing resource usage according to Karimi et al., 2023 and Pineda-Martos et al., 2024. The circular management of debris reduces landfill dumping and reveals potential resource materials (Almusaed et al., 2024). Scientists have developed UV photocatalysis as an innovative waste treatment method to enhance recovery efficiency (Perera (Ma et al., 2021). Minor cycles enable recovery systems along with stakeholder organizations to develop greater resilience according to Karman et al. (2024). The high initial expenses together with stakeholder engagement create barriers to circular economy adoption in sustainable recovery according to Dube (2020).

3.4 Stakeholder Collaboration

The disaster response implementation of CE relies on stakeholder management principles to combine multiple interests and contributions for solving sustainability issues. The system allows stakeholders to work together on environmental problems through broad involvement from all participants (Oberholzer & Sachs, 2023). Different institutions' logic will not impact stakeholder cooperation when value-consolidation mechanisms maintain their mutual goals and behaviors suitable for joint work (Vikstedt & Rajala, 2023). The development of common strategies for sustainability enhancement relies on collective governance through organization models which include company-centric and industry-oriented and cross-industry segments (Oberholzer & Sachs, 2023). The integration between construction and renewable energy within the system demonstrates environmental benefits together with economic returns (Almusaed et al., 2024). Stakeholder engagement requires universal adaptive mechanisms to overcome current conflicting interests so both parties achieve intended goals.

4. Conclusion

The implementation of Circular Economy principles in disaster recovery establishes an innovative approach to handle linear recovery process issues alongside growing global interests in sustainable solutions. The concepts that make up resource efficiency and material reuse alongside ecosystem restoration enable CE to build reconstruction that promotes sustainability and resilience. A limited application of CE principles during disaster recovery indicates both stakeholders must work together to develop research that will bridge the two concepts. Review findings show that CE delivers waste reduction together with sustainability promotion and it helps enhance life-cycle thinking while addressing socio-economic disparities. New CE-based strategies for addressing disaster response challenges in climate change and growing populations require information from the study results to guide the development activities of policymakers and researchers alongside practitioners.

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CLIMATE-SMART AGRICULTURE FOR A RESILIENT AND FOOD-SECURE FUTURE

ICSD 047

ASSESSMENT OF TIMBER AUTHENTICITY IN SRI LANKA: A CASE STUDY ANALYSIS

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Abstract: Timber is regarded as an ecological friendly versatile green building material with less required construction energy. In Sri Lanka there are over 450 different timber species, which show a wide range of variation in their physical properties as well as their anatomical structures. Hence timber identification is a highly important task to confirm its authenticity. As consumers are not identified timber species correctly and they tend to get misled easily. The objective of this study is to investigate the authenticity of local and imported timber species used in Sri Lanka. In this study 190 timber identification reports (local and imported) were studied. These reports were issued by the State Timber Corporation to various timber users and companies during the past three years (2021, 2022 & 2023) after identifying the status of authenticity of timber samples. Anatomical features of given wood samples were observed by preparing a permanent slide using cross section, radial section and tangential section. According to microscopic examination of the slides, timber authenticity was investigated. According to the results, there were 145 local timber samples claimed by end users among 190 total samples. Out of 46 timber species 38 timber species were local species. Out of 38 local timber species, it was found that ten local timber species claimed by end users were 100% correct (authentic): Donga, Imbul, Jack, Milla, Paramara, Pelen, Tuna and Yakahalu. But claims for 31 local species were incorrect or not identified: Acacia, Bedidell, Grandis, Halmilla, Hora, Kumbuk, Liyan, Mahogany, and Ginisapu etc. Acacia was incorrectly claimed as Teak. They claimed Bedidel for Jack and Liyan for Dun. From 46 timber species, eight were imported timber species. Merbau is the only timber species in the samples that is associated with 100% of correct (authentic) end user claims for the sample. Kempas and Tualang were 21.05 % and 26.67 % authentic. And end users claimed 100% incorrectly with Bitis and then claimed Kempas. End users were also wrongly claiming Tualang as Kempas. The local and imported timber species revealed very low authenticity percentages, and the local species has higher authentic percentage than imported timber species.

Keywords: Authenticity; Timber, Local and imported; Timber identification

1.Introduction

Illegal timber trade is a major global issue that has negative environmental, economic, and social impacts in the world (Nellemann & INTERPOL 2012; Hoare 2015; Vijay et al. 2016). With regards on the timber market, some timber merchants sell low grade timber species which are below the accepted standards and norms because the buyers are not able to identify the authenticity and quality of the timber species. Hence, they are easily misled by timber authenticity (IAWA,2013; Muthumala, Arunakumara and Basnayake, 2019). Physical properties and mechanical properties are very important in case of structural and nonstructural purposes of timber. The properties not only vary with species but also with the moisture content, density, porosity etc (Muthumala, 2019). Nearly 450 different timber species of wood are found in Sri Lanka (Muthumala et al, 2021) and this timber species show a remarkably wide range of variation in their physical properties as well as their anatomical structures. Previous research study found that some timber species supplied by the dealers as high rated timbers, (e.g. Durian) had comparable density values with that of true species (e.g. Balau and Kempas) but these species were less durable compared with the true species (Tariq and Amarasekara, 2000). Hence timber Identification is a highly important task to confirm its authenticity.

This prevailing situation can be minimized if a standard mechanism is introduced for timber identification. The State Timber Corporation (STC) has received the authority to issue timber identification report by Special Gazette notification (Gazette 1538/7, 2008). Proper timber identification mechanism is essential today than ever before as lesser-known timber species are coming to present timber market. Recent research study indicate that all priority taxa can be identified at least to genus with wood anatomy (IAWA, 2013). According to previous survey conducted by the State Timber Corporation, Sri Lankan timber users have higher authentic rate for local timber than imported timber (Siriwardana and Muthumala, 2018; Muthumala and Amarasekara, 2013).

Main objective of this study is to investigate the authenticity of local and imported timber species used in Sri Lanka.

2.Methodology

One hundred and ninety-three timber identification reports (Local and Imported) which were received to STC from year 2021 to 2023 were studied to study the status of the authenticity. All the reports were prepared after the observation of the anatomical features of given wood samples according to standard method given below.

2.1 Preparation of wood for microscopic examination

Wood samples were boiled in water periodically for three days until air space of wood was occupied with water. Each sample was shaped and sized into wood block of 20 mm x 20 mm x 30 mm. Transverse, radial and tangential section at the range of 10-15 micrometer thickness were taken using a sledge Microtome (Model Leica SM2000 R). The piece of wood sample and the knife were flooded with 30 % ethanol, during the section cutting to facilitate fine sectioning. Wood sections were rinsed in alcohol series, stained in safranin, dehydrated and mounted permanently using Canada balsam. Thin wooden samples were flooded in 50% alcohol for five minutes for the dehydration of the section. Then samples were transferred to another petri dish with Safranin and 50% alcohol for 15 minutes (for removal of the moisture and the colour). Then samples were washed in 50 % alcohol for allowing further dehydration and transferred them to a petri dish with 70% alcohol for 5 -10 minutes to remove moisture. Next petri dish with 90% alcohol was used to further dehydration process for 10 minutes period. Samples then flooded in absolute alcohol for the period of 10 minutes. (Evaporation was avoided with covering). Then samples were flooded in Absolute alcohol and Xylene mixture for 10 minutes (if milkiness occurring at this stage indicated incomplete dehydration and previous stage should be repeated). After that, samples were flooded in Xylene for 10 minutes (petri

dish should be covered by a lid). Finally, samples were mounted using Canada balsam using (Bass and Zhang 1986).

Anatomical observations on qualitative and quantitative parameters were made under the light microscope at 4 x 10 magnification. Results were obtained using anatomical photos and Micrometrics SE Premium 4 software available at Wood laboratory, Research division of the State Timber Corporation (Figure 1). Timber sample reports were analyzed the categories of correctly claimed, not correctly claimed and not identified by customers.



01. Soaked wood samples in water.



02. Wood sections were taken using Microtome.



03. Staining process.



04. Wood sections were placed to the slides.



05. The slides were mounted in Canada balsam



06. Prepared slides.



07. Slides were Put in a drying oven for 24



08. Anatomical photos were taken by Micrometrics SE premium 4 software.

Figure 1: Wood identification process

3.Results and Discussion

Having the timber identification certificate reports from STC research division, based on the samples which were provided by various clients for past 3 years were summarized in Table 1.

Table 1. Summary details of samples which were provided by various clients by year 2021-2023

Local/Imported	Species Name(Local)	Total No. of Species	Correctly claimed	Not Identified	Incorrect claims	Incorrectly claimed species	Correctly claimed %
Local	1) <i>Acacia</i> (<i>Acacia spp</i>)	4			1	Teak	0
	2) <i>Artocarpus</i> spp	2		2			0
	3) Bedi Dell (<i>Artocarpus</i> spp	1			1	Jack	0
	4) Blue Gum (<i>Eucalyptus globulus</i>)	1		1			0
	5) Camaldulensis (<i>Eucalyptus caaldulensis</i>)	2		2			0
	6) Chengal (<i>Neobalanocarpus heimii</i>)	1		1			0

	7) Dawata (<i>Carallia brachita</i>)	1		1			0
	8) Domba (<i>Calophyllum inophyllum</i>)	3	1	2			33.33
	9) Donga (<i>Sandorica indicum</i>)	2	2				100.00
	10) Ginisapu (<i>Michelia champaka</i>)	1		1			0
	11) Grandis (<i>Eucalyptus grandis</i>)	8	2		6		25.00
	12) Halmilla (<i>Berrya cordifolia</i>)	2	1		1		50.00
	13) Hawarinuga (<i>Alstonia macrophylla</i>)	2		2			0
	14) Hora (<i>Depterocarpus Spp.</i>)	9	3		6		33.33
	15) Imbul (<i>Ceiba pentandro</i>)	1	1				100.00
	16) Jack (<i>Artocarpus spp.</i>)	3	3				100.00
	17) Ketakala (<i>Bridelia retusa</i>)	1		1			0
	18) Kohomba (<i>Azadirachta indica</i>)	1		1			0
	19) Kosgonna/ Gonna	1		1			0
	20) Kumbuk (<i>Terminalia arjuna</i>)	2	1		1		50.00
	21) Liyan (<i>Homalium zeylanicum</i>)	3	1		2	Dun	33.33
	22) Lunumidella (<i>Melia dubia</i>)	2		2			0
	23) Mahogany (<i>Swietenia spp.</i>)	12	3		9		25.00
	24) Micro (<i>Eucalyptus microcorys</i>)	14	3		11	Grandis	21.43
	25) Milla (<i>Vote pinnata</i>)	1	1				100.00
	26) Paramara (<i>Albizia spp</i>)	1	1				100.00
	27) Pelen (<i>Kurrimia ceylanica</i>)	1			1	Liyan	100.00
	28) Redgum (<i>Eucalyptus robusta</i>)	3		3			0
	29) Rubber (<i>Hevea brasiliensis</i>)	1		1			0
	30) Sabukku (<i>Grevillea robusta</i>)	1		1			0
	31) Shorea spp.	8		8			0
	32) Suriyamara (<i>Albizia odoratissima</i>)	11		11			0
	33) Teak (<i>Tectona grandis</i>)	33	9		24		27.27
	34) Tereticornis (<i>Eucalyptus tereticornis</i>)	2		2			0
	35) Toona (Toona spp)	1	1				100.00
	36) Toraliana (<i>Eucalyptus toreliana</i>)	1		2			
	37) Wana mee (<i>Madhuca fulva</i>)	1		1			
	38) Yakahalu	1	1				100.00
	Total	145	34	46	63		22.82
	1) Ananta (<i>Cynometra ananta</i>)	1		1			
Import ed	2) Bitis (<i>Madhuca spp.</i>)	1			1	Kempas	
	3) Kasai (<i>Pometiab sp</i>)	1		1			
	4) Kempas (<i>Koompassia malaccensis</i>)	19	4		15	Taulang	21.05
	5) Merbau (<i>Intsia spp</i>)	1	1				100.00
	6) Red Balau (<i>Shorea spp</i>)	3		3			
	7) Tualang (<i>Koompassia excelsa</i>)	15	4	10	1	Kempas	26.67
	8) Pelewan (<i>Tristanopsis spp.</i>)	4		3	1	Balau	
	Total	45	9	18	18		21.95

There were 145 local timber samples and 45 imported timber samples were considered. According to microscopic examination of the slides, timber authenticity was investigated. According to the results, there were 145 local timber samples claimed by end users among 190 total samples.

Out of 46 timber species 38 timber species were local species. Out of 38 local timber species, it was found that 08 local timber species claimed by end users were 100% correct (authentic): Donga, Imbul, Jack, Milla, Paramara, Pelen, Tuna and Yakahalu. But claims for 31 local species were incorrect or not identified: Acacia, Bedidell, Grandis, Halmilla, Hora, Kumbuk, Liyan, Mahogany, and Ginisapu etc. Acacia was incorrectly claimed as Teak. Bedidel was claimed as Jack and Liyan was claimed as Dun.

Out of 45 timber species, there were only eight imported timber species. In these samples, Merbau timber sample is 100% of correct (authentic) end user claims, but only one sample was considered. Authenticity percentages of Kempas and Tualang were, 21.05 % and 26.67 % respectively. Bitis was 100% incorrectly claimed and it was claimed as Kempas by end users. Tualang was incorrectly claimed as Kempas by end users also. Similar trends were recorded in previous studies published by Siriwardena and Muthumala in year 2018 and Muthumala and Amarasekara in year 2013.

4.Conclusions

According to the results, authenticity percentage are very low both local and imported timber species. Local timber species has a higher authentic percentage compared to imported timber species. Some timber merchants sell low grade timber species which are below the accepted standards and norms because the buyers are not able to identify the authenticity and quality of the timber species. Hence It is needed to be checked the timber authenticity prior to use of them in construction works by tested wood samples from authorized laboratory.

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ICSD 048

**STAKEHOLDERS IN FLOOD RISK MANAGEMENT: A CASE STUDY OF THE
NILWALA RIVER IN SRI LANKA****W.N.K Hapuwaththa* , H.M.M Herath***Department of Town & Country Planning, Faculty of Architecture, University of Moratuwa, Sri Lanka.***Correspondence E-mail: malani@uom.lk, TP: +94714569017*

Abstract: In recent decades, Flood Risk Management (FRM) has undergone a paradigm shift, as reflected in the evolution of policies and strategies. This shift emphasizes the adoption of proactive, integrative approaches that prioritize nature-based solutions and long-term sustainability. Traditionally, FRM followed a top-down model, with central authorities controlling resources and assuming responsibility for regulations and enforcement. However, this centralized approach often overlooks local needs and prompts calls for more inclusive and integrated governance. Recent developments in FRM highlight the importance of multiscale and polycentric governance, with a growing emphasis on bottom-up initiatives and active stakeholder participation. In this context, local stakeholder engagement is critical. Yet, limited experience with implementing such integrated approaches poses challenges and barriers to their success. This study aims to deepen our understanding of stakeholder interactions within the flood risk management system. This study focuses on the Nilwala River Basin in Sri Lanka as a case study to explore stakeholder dynamics in flood risk governance. The Nilwala River is located in the wet zone of Sri Lanka, and the river basin is highly vulnerable to flooding, particularly in low-lying areas. These flood events pose a significant and recurring threat to communities, livelihoods, and local infrastructure. In recent years, the combined effects of climate change, land use transformations, and inadequate flood management have intensified both the frequency and severity of flooding in the region. The stakeholder analysis identified key actors involved in flood risk and river basin management. Using Social Network Analysis (SNA), supported by structured questionnaires and visualized through Gephi, stakeholder interactions were mapped across three networks: communication, ecological status, and flood risk. Findings reveal a concentration of influence among government agencies, indicating strong but largely mandated connections within the network. However, the limited involvement of stakeholders from the economic sector and local communities suggests a gap in cross-sectoral collaboration, which could hinder the development of integrated flood risk management strategies.

Keywords: Flood Risk; Governance; Stakeholders; Collaboration; Nilwala River

1. Introduction

1.1 Flood resilience

In recent years, the traditional understanding of flood resilience, primarily centered on a community's ability to maintain functionality in the face of shocks, has been significantly reevaluated. The contemporary definition of resilience has broadened to include not only the capacity to endure and recover from disruptive events but also the ability to proactively engage with, adapt to, and influence ongoing changes, all while coexisting with uncertainty. As a result, flood resilience is increasingly viewed as a dynamic phenomenon that provides multiple pathways to achieving resilience, including persistence, transition, and transformation (Meerow et al., 2016). Decision-making is naturally shaped by varied perspectives and interpretations regarding the structure of the problem, its variables, and how they interrelate (Brugnach, 2023). Resilience has developed into what is known as a "boundary object" or bridging concept, which effectively supports interdisciplinary communication, helps coordinate different groups of actors or stakeholders, and builds consensus around specific policy issues, as noted by Baggio (2015) and Brand (2007).

1.2 Flood risk management strategies.

In the context of climate change and rising flood risks, the limitations of resistance-based flood risk management strategies have become more evident. Levees built along riverbanks, for example, further separate rivers from their floodplains, disrupting natural floodplain connectivity and diminishing ecosystem services. Additionally, these strategies create a false sense of security—a phenomenon known as the "safe development paradox." This perceived safety leads to increased property investment in flood-prone areas, ultimately raising the potential damage risk if levees fail (Blázquez et al., 2021). In a narrow sense, flood risk management focuses on handling existing flood risks through mitigation efforts such as flood defenses and emergency response plans. In a broader sense, however, it includes proactive planning and the development of systems and strategies to reduce future flood risks. This broader approach involves long-term infrastructure upgrades, sustainable land-use planning, and ecosystem-based methods to lessen the impacts of floods (Plate, 2002). In recent decades, water management has been shifting its approach, and nature-based solutions are gaining popularity (Hartmann et al., 2019). The concept of 'Nature-based solutions' was introduced towards the end of the 2000s by the World Bank and International Union for Conservation of Nature (IUCN) to highlight the importance of biodiversity conservation for climate change mitigation and adaptation.

Implementing Nature-based Flood Risk Management (NFM) presents significant challenges (Thaler et al., 2023). Unlike traditional flood management, which relies on localized, infrastructure-based solutions, NFM requires large-scale, catchment-wide interventions. This broader approach necessitates collaboration across diverse geographic and political boundaries and the involvement of multiple stakeholders to achieve meaningful risk reduction and foster cooperation between upstream and downstream areas. A primary challenge lies in the potential inequity for upstream landowners, who may need to implement flood mitigation measures that primarily benefit downstream communities. This scenario highlights the need for either acceptance of potential losses or appropriate compensation to incentivize upstream landowner cooperation. Additionally, evaluating trade-offs in ecosystem services helps determine an optimal balance between the costs and benefits of environmental resource use for communities (Giordano, 2022).

1.3 Importance of social capital

The benefits of nature-based flood management (NFM) are often less tangible and more challenging to measure, making its implementation dependent on transformative changes in governance, mindset, and practice. This shift requires a more inclusive approach that actively involves all relevant stakeholders in the

co-design and co-implementation of management measures. As a result, stakeholder collaboration and grassroots, bottom-up initiatives become essential (Knighton et al., 2018). Social capital is crucial in this process, as effective collective action relies on strong networks and information flows among stakeholders, policy makers, and decision-makers. These connections determine the extent to which decision-making can be effectively guided by local stakeholders (Ostrom, 1998).

1.4 Community-Led Governance for Flood Resilience

In climate change policy, strategies should address both sudden, extreme events—such as wildfires, droughts, floods, and heatwaves—and the longer-term interactions between climatic and socioenvironmental processes. Over recent decades, various governance models have emerged to tackle climate and environmental challenges. These range from traditional governance structures, like markets, communities, and government regulations, to hybrid approaches, such as public– private partnerships, concessionary mechanisms, and community-based interventions (Morrison et al., 2017). Community-based, locally led interventions are specifically designed to empower local communities. These models rely on local leaders and residents to implement solutions tailored to the unique environmental challenges of their area. Examples include locally organized reforestation projects, sustainable agricultural practices, and disaster resilience training. This model is especially effective because it combines local knowledge with empowerment, enabling communities to take ownership of environmental initiatives.

The socio-economic impacts of climate change affect all scales and sectors; however, vulnerable communities at the local level bear the greatest burden. Households and communities are on the front lines, directly confronting climate-induced challenges. This underscores the importance of understanding and supporting local adaptation efforts, as most effective solutions will be identified and implemented at this level. While adaptation is a global challenge requiring collective responsibility, this reality highlights the urgent needs that must be addressed and the local capacities that should be strengthened to facilitate substantial adaptation on a broader scale (Mfitumukiza et al., 2020).

1.5 Polycentric governance models for management of flood risk

In monocentric governance, a single state authority holds the power to make decisions and implement policies. This central authority often has comprehensive control over resources, regulations, and enforcement mechanisms. Decision-making flows from the top down, which can lead to efficient implementation of policies but may also overlook local needs and conditions. Polycentric governance consists of numerous governing entities that operate independently at various scales (local, regional, national, and international). This decentralized nature allows for more diverse approaches to problem-solving. Unlike monocentric systems, polycentric systems emphasize non-hierarchical relationships where different actors, including public and private entities, interact collaboratively without a central authority dominating the process. These systems promote learning from shared experiences and emphasize coordination among various stakeholders. This can enhance flexibility and resilience in governance. By allowing for self-organization and collective decision-making, polycentric systems can respond more effectively to local conditions and emerging challenges. This adaptability is crucial in complex and dynamic environments (Morrison et al., 2017). Monocentricity and polycentricity represent two extremes on this continuum, with various systems existing between them. A strong polycentric order is characterized by a significant dispersion of power among multiple governing entities. Polycentric governance is increasingly recognized as a vital approach for addressing the complexities of climate change.

1.6 Floods in the Nilwala River

The Nilwala River basin covers approximately 1,032 km² in the southern region of Sri Lanka, situated within the country's wet zone. The slope angles in the basin range from 0 to 62 degrees. The upper reaches of the catchment experience a mean annual rainfall of about 3,000 mm, while the lower reaches receive approximately 1,900 mm (Panditharathne et al., 2022). Most rainfall occurs between March and June and again from August to December, with average monthly totals exceeding 200 mm (Abey Siriwardana & Wijesekera, 2022). Low-lying areas within the Nilwala River valley, including the Matara, Malimbada, Kamburupitiya, Thihagoda, Athuraliya, and Akurassa Divisional Secretariats in Matara district, face significant threats from major flooding situations. Many of the current flood risk management measures in the Nilwala River Basin—such as river clearing, widening the river mouth, and water pumping in low-lying areas—are primarily resistance strategies designed to mitigate the impacts of flooding. In recent years, Sri Lanka has experienced a significant increase in both the frequency and intensity of rainfall during monsoon seasons. This trend has led to a higher incidence of flooding, particularly in areas undergoing considerable land use transformation. Consequently, these floods have caused substantial property damage and disruptions to economic activities.

Table 1: Areas with the Highest Flood Exposure in Matara District during peak events

Disaster Affected					Damage of Houses		Other Property Damage
No.	DSD	GNDs	No. of Affected Families	No. of Family Members	Total Damages	Partial Damage	
1	Akuressa	Paradoowa South, Yakabedda	1,250	5,000	N/A	16	32
2	Athuraliya	Wenagama, Hawupe, Godapitiya	2,370	7,793	N/A	15	1
3	Kamburupitiya	Karagoda North, Gathara North	1,155	4,315	N/A	30	N/A
4	Malimbada	Malimbada South, Kiyaduwa	1,395	4,786	N/A	3	N/A
5	Matara	Weradoowa, Thudawa South	2,074	9,333	3	109	3
6	Thihagoda	Watagedara, Wellethota	3,908	12,254	N/A	35	N/A

Table 2: Annual Rainfall Distribution at Matara District-Part 1

Year	January	February	March	April	May	June
	<i>Rainfall (mm)</i>	<i>Rainfall (mm)</i>	<i>Rainfall (mm)</i>	<i>Rainfall (mm)</i>	<i>Rainfall (mm)</i>	<i>Rainfall (mm)</i>
2008	127.5	208.3	168.1	248.2	200.9	212.4
2013	141.5	121.3	69.3	0.6	280.4	191.3
2018	53.5	145.8	96.7	146.7	300.0	208.1
2023	35.8	120.8	80.8	105.8	324.8	156.1

Table 3: Annual Rainfall Distribution at Matara District-Part 2

Year	July	August	September	October	November	December	Annual Rainfall
	<i>Rainfall (mm)</i>	<i>Rainfall (mm)</i>	<i>Rainfall (mm)</i>	<i>Rainfall (mm)</i>	<i>Rainfall (mm)</i>	<i>Rainfall (mm)</i>	<i>Rainfall (mm)</i>
2008	208.0	205.9	46.1	359.8	336.8	127.5	2449.5
2013	182.2	10.2	200.4	257.1	186.6	52.3	1693.2
2018	55.1	68.9	53.7	219.8	112.4	91.7	1552.4
2023	70.1	78.0	786.2	896.9	27.0	N/A	2682.3

Malimbada, identified as the divisional secretariat division with one of the highest flood risks in the Nilwala riverine area, was the focus of this study. It comprised 29 Grama Niladhari divisions and had a population of 37,409. Malimbada operated on an agro-based economy, with an asweddumized paddy cultivation area spanning 1,291.3 hectares. As highlighted in Figure 01, the region receives a significant amount of rainfall during the southwest monsoon period. Factors contributing to its vulnerability included ongoing population growth, unauthorized land reclamation driven by political influence, subsequent infrastructure development, and unexpected shifts in rainfall patterns. This complex interplay of factors left the region susceptible to damage even from minor flooding events. Malimbada has been identified as a highly flood-prone area, with over a thousand families frequently affected by flood-related damage during peak events. The most recent flood event, which occurred on 8 October 2023, impacted 1,395 families in the Malimbada South and Pahala Kiyaduwa Grama Niladhari Divisions (Table 01). Inadequate flood management measures further exacerbated the challenges, making Malimbada a consistently distressed region during nearly every flood event.

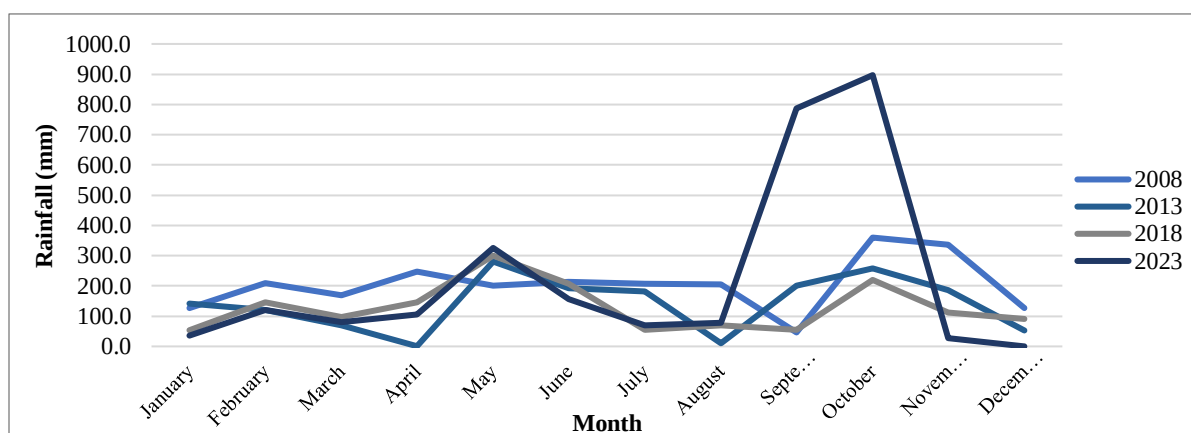


Figure 1: Rainfall distribution at Thalgahagoda station in Matara district (2008-2023) / Source: Zonal Irrigation Office-Matara

2. Research objectives

Flood risk mitigation often necessitates collective action among interdependent actors who share exposure to hazards. Scholars have highlighted the significance of understanding how governance systems self-organize through collaborative interactions among policy actors. This research specifically investigates stakeholder involvement in the flood risk management system, aiming to identify the arrangement of stakeholders within the current river management process and to examine their interconnections. The Research Objective of this study is to identify the key stakeholders involved in flood risk management and examine the relationships and connections among them.

3. Methodology

3.1 Stakeholder analysis

Malimbada has been identified as the Divisional Secretariat with the highest flood risk in the Nilwala riverine area, making it the focal point of this study. The stakeholder analysis, conducted in three stages, commenced with a primary focus on identifying key stakeholders involved in management and conservation. Employing a dual approach, namely ex-ante and ad-hoc methods, the ex-ante strategy proactively categorized stakeholders through a literature review and expert insights, resulting in an initial stakeholder list. This comprehensive methodology ensured a thorough identification of stakeholders engaged in the management, conservation, and exploitation of fluvial systems within the study area. In the second stage, finalized stakeholders are visually represented in a network to illustrate their relationships using Social Network Analysis (SNA), grounded in mathematical graph theory (Wasserman and Faust, 1995). Initially, three river networks ("talk network," "ecological status network," and "flood risk network") were established from dual perspectives to enhance precision (Blázquez, García, and Bodoque, 2021). The talk network refers to the interactions and communication channels among stakeholders involved in river management. The ecological status network focuses on the relationships and interactions among stakeholders concerning the ecological health and integrity of river systems. The flood risk network encompasses the connections and collaborations among stakeholders, specifically focused on assessing, managing, and mitigating flood risks.

The questionnaire was organized into three sections, following the methodologies outlined by Lara et al. (2010) and Blázquez et al. (2021). The first section included ten items that assessed the effectiveness of flood risk mitigation measures, rated on a five-point Likert scale. This section also contained a yes/no question regarding each organization's specific interest in the river. The second section comprised three inquiries related to stakeholder discussions about the overall river status, ecological condition, and flood risk frequency. The responses generated three 39 x 39 matrices for Social Network Analysis (SNA). Before conducting the SNA, an evaluation of communication frequency consistency was performed, replacing disparate values with the minimum reported by two counterparts, which resulted in three symmetric matrices. The third section collected sociodemographic details about the key informants, including age, gender, education level, represented organization, and position.

3.2 Stakeholder Relationship Analysis: Social Network Analysis (SNA)

Social Network Analysis (SNA) is a powerful methodological framework grounded in mathematical graph theory (Wasserman and Faust, 1995). It serves as a vital tool for understanding the relationships and interactions among various social entities, including individuals, groups, and organizations (Yang and Yang, 2014; Tabassum et al., 2018; Boyle et al., 2021). By representing these entities as nodes and their connections as edges in a graph, SNA allows researchers to visualize and analyze the complex web of relationships that exist within a network. This analysis is instrumental in identifying the degree of involvement, collaboration, and influence of each stakeholder, revealing how interconnected or isolated

they are within the network (Zedan and Miller, 2017). Ultimately, SNA facilitates a deeper understanding of the dynamics at play within a community or organizational structure, highlighting patterns of connectivity and collaboration that are crucial for effective decision-making and resource allocation. The social network analysis was conducted using Gephi, an open-source software specifically designed for visualizing and analyzing large networks and complex systems.

4. Results

4.1 List of the stakeholders in the flood risk management process

Central Environmental Authority (CEA), Ceylon Electricity Board (CEB), Department of Meteorology (DM), Department of Agriculture (DA), District Secretariat (DS), Divisional Secretariat Malimbada (DSM), District Disaster Management Center Unit (DDMCU), Bureau of Geological Survey and Mining (GSM), Farmers' Organization (FOs), National Water Supply and Drainage Board (NWSDB), National Building Research Organization (NBRO), Sri Lanka Police-Matara (SLP), Pradeshiya Sabha-Malimbada (PS), Road Development Authority (RDA), Red Cross (RC), Security Forces (SF), Survey Department-Matara (SDM), Sri Indrarama Purana Viharaya-Malimbada (SIPVM), Urban Development Authority (UDA), Zonal Irrigation Office-Matara (ZIOM), District Irrigation Office-Matara (DIOM), Sri Lanka Telecom (SLT), Department of Fisheries & Aquatic Resources (DFAR), Development of Agrarian Development (DAD), Ceylon Transport Board (CTB), Southern Province RPTA, Sri Lanka Railway Department (SLRD), Regional Director of Health Services Office-Matara (RDHS), Department of Posts (DP), Coast Conservation & Coastal Resource Management Department (CCCRMD), Department of Forest (DF), Department of Cooperative Development (DCD), National Housing Development Authority (NHDA), Sri Lanka Radio (SRR), Land Use Planning Department (LUPD), Non-Governmental Organizations (NGOs), University of Ruhuna (UR), Lanka Hydraulic Institute (LHI), and Rice Millers (RM) are various key organizations and bodies involved in the process.

The stakeholders were classified into the four groups mentioned above: i) national interventions, ii) decision-makers, iii) civil society, and iv) economic sectors. This categorization helped identify the various roles and responsibilities that each group had in managing the Nilwala River Basin. The following Figure 02 indicates the stakeholders in the flood risk management process.

4.2 Social network analysis

In social network analysis (SNA), stakeholders are represented as nodes (or vertices) within a network, while the relationships between them are depicted as edges (or links). This type of visualization helps analyze the structure, strength, and dynamics of relationships among stakeholders, making it easier to understand the network's characteristics. The stakeholders were visually represented in a network using Social Network Analysis (SNA), grounded in mathematical graph theory. In this network graph, each stakeholder is depicted as a vertex, with lines indicating their relationships. Three river networks—the "talk network," "ecological status network," and "flood risk network"—were created to enhance accuracy. Weighted networks, based on stakeholder responses, were carefully analyzed to develop a comprehensive understanding of the relationships within these river networks.

The talk network highlights the interactions between stakeholders, focusing on the exchange of information among them. It emphasizes how often and to what extent stakeholders engage with each other in communication. In managing the complexity of flood risk, effective communication within the talk network can play a crucial role in facilitating collaboration, enhancing decision-making processes, and ensuring that stakeholders are well-informed and aligned in their efforts. A flood risk network refers to a network that represents the relationships, interactions, and communication channels between various stakeholders involved in flood risk management. An ecological network refers to a system of interconnected stakeholders and entities focused on managing and preserving the environment, ecosystems, and biodiversity. Table 3, along with Figure 3,4,5 & 6 presents a comprehensive view of the network characteristics, highlighting the key features of the network.

Table 4: Topological measures of the stakeholder network

Indicator	Talk	Ecological status	Flood risk
Lines	410	197	254
Density	0.553	0.423	0.342
Average degree	21.026	12.71	13.026
Closeness centrality (Average)	0.709	0.661	0.613
Betweenness centrality (Average)	8.487	9.454	14.833
Clustering coefficient (Average)	0.781	0.793	0.782
K-core	(k=16) 22	(k=11) 17	(k=11) 18

Source: Done by the Author by referring to the article “Stakeholder analysis: Mapping the river network for integrated flood risk management” (Blázquez, García, and Bodoque, 2021)

The Talk Network has the highest density value of 0.553, indicating a relatively high level of connectivity among stakeholders. This suggests that communication and interaction among stakeholders in the talk network are more frequent and well-established, allowing for better collaboration and exchange of information.

a. Network structure

The dimensions of the nodes (representing stakeholders) are determined by their cumulative number of links (all node degrees). Stakeholders who are highly connected will have larger nodes, visually signaling their significance and central role in the river network. Stakeholders with fewer connections will have smaller nodes, indicating they are less connected or influential within the network. The below Figure 03,04 & 05 indicate that highly connected stakeholders are positioned at the center, engaging with a greater number of other actors, while the majority of stakeholders on the periphery have minimal partners, most of whom are central stakeholders.

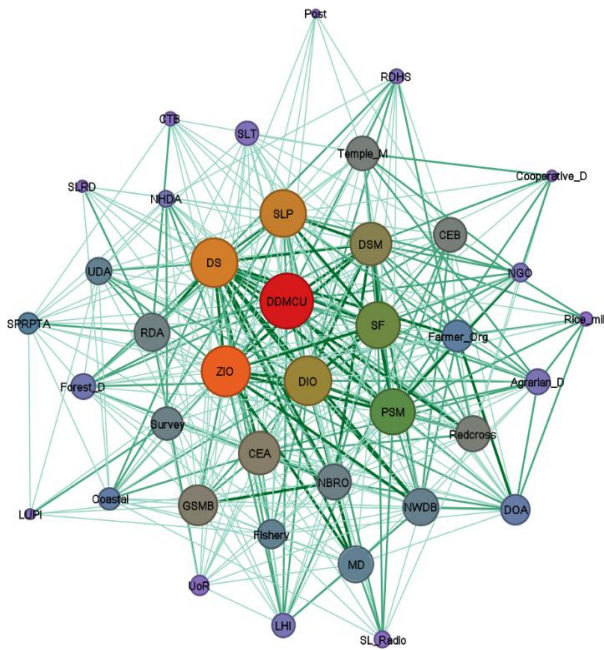


Figure 3: Structure of the Talk Network (Source: Prepared by Author using Gephi 0.10)

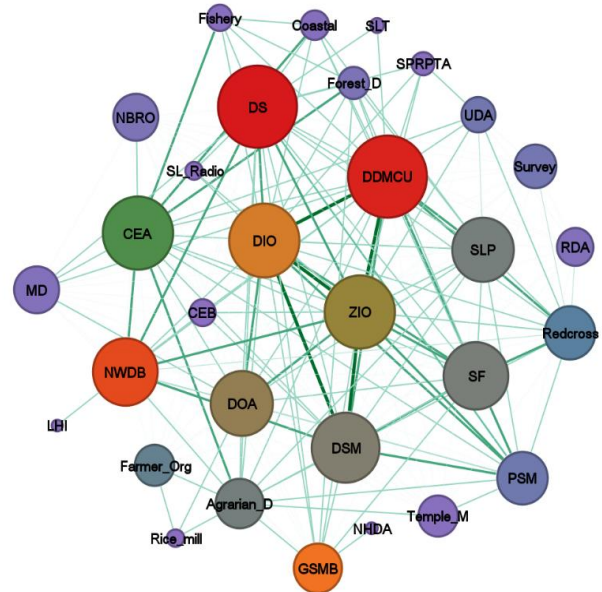


Figure 4: Structure of Ecological Status Network (Source: Prepared by Author using Gephi 0.10)

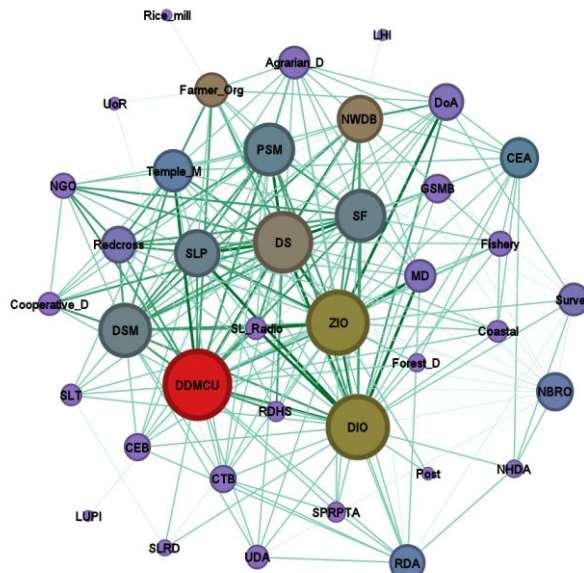


Figure 5: Structure of the network of Flood Risk Management (Source: Prepared by the Author using Gephi 0.10)

Around 80% of potential triangular relationships are observed among stakeholders, indicating a high level of clustering around central actors across all three networks. Relatively dense subnetworks and cohesive subgroups have been identified. In the talk network, a large subnetwork of 22 stakeholders is strongly interconnected, including national intervenors, decision-makers, and civil society members. In contrast, the ecological status and flood risk networks have smaller, dense subnetworks (18 stakeholders), with nearly identical participants, except for a few differences, highlighting strong relationships among key actors. The economic sector shows minimal participation in all three networks.

K-cores signify the most compact subnetwork within each network, where the node sizes are proportionate to their overall number of links. It indicates the largest subnetwork in which every node maintains a degree of at least k. The above figures highlight 22 stakeholders who are strongly connected with each other.

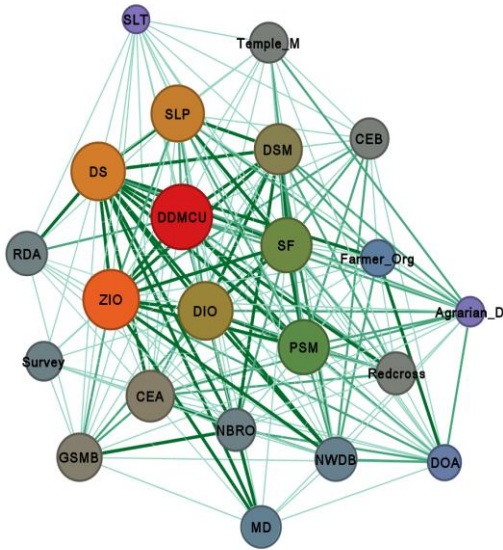


Figure 4: Talk Network (k=16)

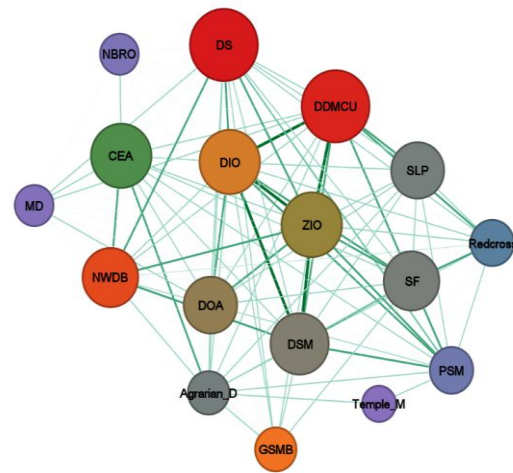


Figure 5: Ecological Status Network (k=11)

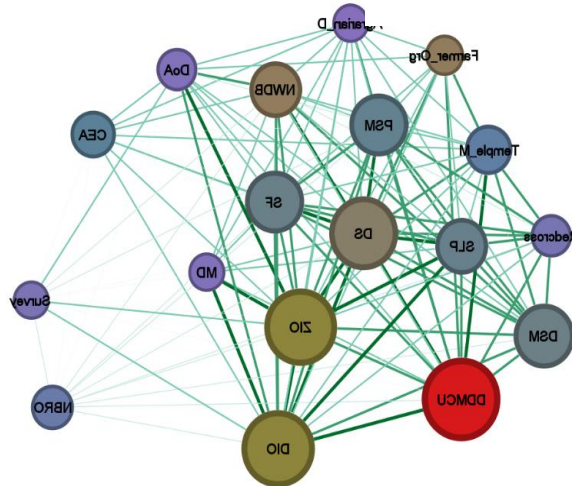


Figure 6: Flood Risk Network (k=11)

As highlighted in Figures 4, 5, and 6, the Social Network Analysis revealed weak relationships among stakeholders within river networks, hindering collaborative decision-making. It emphasized the importance of connected stakeholders for successful strategy implementation. The involvement of local stakeholders in decision-making processes was essential, requiring awareness, capacity, resources, and social capital. At that time, most local stakeholders (particularly government ones) were not well connected within the network. To address this, the first step was to raise awareness among disconnected local stakeholders about their role in the river network and their potential impact on related issues. National and regional authorities were positioned as leaders in the decision-making process, defining conditions and objectives, integrating stakeholders into the Bottom-Up Involvement (BUI) approach, and fostering collaboration. The success of this strategy depended on political willingness, flexibility, and trust-building, particularly among stakeholders who had not collaborated before.

4.4 Key Stakeholders in the Social Structures

Talk network

- I. Central Environmental Authority (CEA)
- II. District Disaster Management Center Unit-Matara (DDMCU)
- III. District Irrigation Office-Matara (DIO)
- IV. District Secretariat-Matara (DS)
- V. Divisional Secretariat-Malimbada (DSM)
- VI. Geological Survey and Mines Bureau (GSMB)-Matara
- VII. Pradeshiya Sabha-Malimbada (PSM)
- VIII. Security Forces (SF)
- IX. Sri Lanka Police (SLP)
- X. Zonal Irrigation Office-Matara (ZIO)

Ecological Status Network

- I. Central Environmental Authority (CEA)
- II. District Disaster Management Center Unit-Matara (DDMCU)
- III. District Irrigation Office-Matara (DIO)
- IV. District Secretariat-Matara (DS)
- V. Divisional Secretariat-Malimbada (DSM)
- VI. National Water supply & Drainage Board (NWDB)
- VII. Security Forces (SF)
- VIII. Sri Lanka Police (SLP)
- IX. Zonal Irrigation Office-Matara (ZIO)

Flood Risk Management Network

- I. District Disaster Management Center Unit-Matara (DDMCU)
- II. District Irrigation Office-Matara (DIO)
- III. District Secretariat-Matara (DS)
- IV. Divisional Secretariat-Malimbada (DSM)
- V. Pradeshiya Sabha- Malimbada
- VI. Security Forces (SF)
- VII. Sri Lanka Police (SLP)
- VIII. Zonal Irrigation Office-Matara (ZIO)

5. Discussion and Conclusion

The study identified the key participants involved in flood risk management within the Nilwala River Basin and analyzed their connections using Social Network Analysis (SNA). The findings reveal that networks exhibit strong connections, primarily driven by mandatory relationships, with government actors playing a dominant role in decision-making and implementation. Their authority and resources enable them to shape policies, coordinate responses, and implement measures to mitigate flood risks effectively. However, the involvement of the economic sector and civil society remains notably low, highlighting a gap in collaboration between public institutions and private stakeholders. This lack of engagement may limit the development of comprehensive and sustainable flood management strategies. Furthermore, awareness and interest in Nature-Based Solutions (NBS) are limited, despite their potential to enhance resilience. Institutional mandates also show significant disparities, which could hinder coordinated efforts. Addressing these challenges requires fostering greater stakeholder collaboration, integrating Nature-Based Solutions, and enhancing institutional synergy. A more inclusive and multi-sectoral approach can strengthen flood risk management, ensuring a resilient and adaptive response to future flood threats. Therefore, it can be recommended to establish formal platforms for negotiation between the government sector and local communities in operationalizing Nature-Based Solutions (NBS) for flood risk management. Aligning institutional mandates through a coordinated policy framework can reduce fragmentation and enhance collaboration efficiency. This, in turn, will facilitate more locally grounded and sustainable flood risk management.

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ICSD 053

GROWTH AND YIELD RESPONSE OF TURMERIC (*Curcuma longa* L.) TO VARYING TEMPERATURE AND RELATIVE HUMIDITY UNDER OPEN FIELD AND GREENHOUSE CONDITIONS**W. M. C. S. Jayaweera¹, S. R. Amarasinghe², A. L. Ranawake^{3*}**¹Faculty of Graduate Studies, University of Ruhuna, Matara, Sri Lanka²Department of Soil Science, Faculty of Agriculture, University of Ruhuna, Mapalana, Kamburupitiya, 81100, Sri Lanka³Department of Agricultural Biology, Faculty of Agriculture, University of Ruhuna, Mapalana, Kamburupitiya, 81100, Sri Lanka

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Abstract: Environmental conditions play an important role in growth and yield of turmeric (*Curcuma longa* L.). The objective of this study was to evaluate the agronomic performance and yield potential of turmeric cultivated under two different growth conditions in a pot experiment: open field and greenhouse. The average temperature in the greenhouse during the cultivation season was 38.23°C, ranging from 36.98°C in January 2022 to 39.15°C in February and September 2021. The relative humidity varied 65.59% - 66.84% in the greenhouse, while it was 65.95% - 67.43% in the open field. Key parameters including plant height (cm), number of leaves per plant, number of tillers per plant, leaf width (cm), leaf petiole length (cm), number of mother rhizomes, number of primary and secondary fingers, fresh yield per plant (g), and canopy biomass (g plant⁻¹) were assessed. Results revealed significant differences ($p < 0.05$) between the two conditions. Greenhouse-grown plants exhibited significantly greater height (100.62 cm) and significantly wider leaves (10.95 cm). In contrast, open field cultivation produced significantly greater fresh yield per plant (561.80 g), canopy biomass (274.30 g), number of tillers (2.70), number of mother rhizomes (2.70), and number of secondary fingers (89.30). Other parameters, such as the number of primary fingers and leaf petiole length, showed no significant differences. The data show that the combination of higher temperature and slightly lower relative humidity under greenhouse conditions resulted in significantly reduced reproductive traits and yield. This suggests a negative interaction effect between temperature and RH on productivity, despite increased plant height and leaf width. This information is important to optimize turmeric yield.

Keywords: Greenhouse; Growth parameters; Open field; Temperature; Turmeric

1. Introduction

Turmeric (*Curcuma longa* L.) holds immense significance in global agriculture and trade. Turmeric is cultivated in tropical and subtropical regions in countries such as India, China, and Thailand, which are major contributors to its global production (Meena, 2015; Mirjanaik and Vishwanath, 2020; Kumar et al., 2024). It is a component in culinary, medicinal, cosmetic, and dye industries (Filho et al., 2021; Narendhiran et al., 2024). A primary factor behind turmeric popularity is its bioactive compound, curcumin, renowned for its anti-inflammatory, antioxidant, and anticancer properties (Ahmad et al., 2020; Singletary, 2020; Akaberi et al., 2021). These attributes have established turmeric as a traditional medicine and a key spice worldwide.

Environmental factors play an important role in determining the growth and yield of turmeric. Optimal growth of turmeric is achieved in regions with temperatures ranging from 20°C to 30°C and an annual rainfall of at least 150 cm, coupled with well-drained, loamy soils (Prasath et al., 2018). However, deviations from these ideal conditions, particularly due to climate change, can adversely impact plant growth, leaf development, and rhizome yield (Wassmann et al., 2009). Studies have demonstrated that temperature and soil moisture significantly influence sprouting rates, leaf area, and overall plant health. For instance, Ishimine et al. (2004) observed that turmeric rhizomes failed to sprout at temperatures below 10°C or above 40°C, with optimal sprouting occurring between 25°C and 35°C. Similarly, water stress and reduced soil moisture negatively affect the plant morphology, physiology, and yield, highlighting the need for sustainable cultivation practices under varying climatic conditions (Divakaran, 2021). Additionally, changes in irradiance levels and temperature fluctuations directly influence physiological functions, leaf expansion, stem elongation, and rhizome development in turmeric (Hossain et al., 2015; Retana et al., 2021).

Climate change poses a significant threat to agricultural productivity globally, with rising temperatures, unpredictable rainfall patterns, and increasing frequency of extreme weather events adversely affecting crop yields (Allen et al., 2018; Dixon et al., 2018). Turmeric is highly susceptible to these changes, particularly during critical growth stages such as sprouting, bulking, and rhizome development (Daniel-Ogbonna and Okoye 2023). Temperature stress can alter the plant phenology, reduce leaf area, and impair curcumin biosynthesis, thereby diminishing both yield and quality. Research by Ohtaka et al. (2020) and others highlights the role of temperature in regulating plant development, morphogenesis, and overall plant quality.

There is an urgent need to explore adaptive strategies for turmeric cultivation. While open-field systems remain the traditional method of cultivation, greenhouse environments offer a setting where key variables such as temperature, humidity, and soil moisture can be changed compared to open field conditions. Greenhouse cultivation has been shown to mitigate abiotic stresses, enhance plant vigor, and improve yield in various crops (Oyebamiji et al., 2024). However, research directly comparing the performance of turmeric under open-field and greenhouse conditions, particularly in pot cultivation, remains limited. This gap in knowledge delays the development of evidence-based strategies to enhance turmeric productivity under changing climatic scenarios.

Temperature regulation is particularly important for turmeric cultivation due to its influence on phytohormones such as gibberellins (GA) and auxins, which govern key growth processes like stem elongation and cell expansion (Binenbaum et al., 2018; Franklin et al., 2011). These findings suggest that optimizing temperature and light conditions could significantly enhance turmeric growth and development, especially in controlled environments.

Despite its adaptability to diverse agro-climatic zones, turmeric cultivation faces increasing challenges due to climate variability. Although turmeric growth requirements and responses to environmental factors are

well-documented, there is a lack of comprehensive studies comparing its performance in open-field and greenhouse conditions, particularly in the context of pot cultivation. Most existing research focuses on field-based cultivation practices, with limited attention to temperature and humidity. The combined effect of temperature and humidity on turmeric can be tested in greenhouse conditions. This gap in knowledge is particularly significant given the increasing pressures of climate change on agricultural systems. The objective of the present study is to evaluate the growth and yield performance of turmeric in pot cultivation under open-field and greenhouse conditions. The findings will enhance the understanding of environmental requirements of turmeric for practical recommendations for improving its productivity. The results will have important implications to ensure sustainable production in the face of an increasingly variable climate.

2. Materials and Method

This experiment was conducted at the Faculty of Technology, University of Ruhuna, Sri Lanka, from February 2021 to January 2022. The field was located at 6°03'46.8"N and 80°32'29.2"E. The agroecological zone of the field was defined as a low country wet zone with annual rainfall of more than 2500 mm and a mid-day temperature around 31.45 °C. Turmeric rhizomes were collected from a farmer's field in Thellijawila, Sri Lanka. Healthy rhizomes were treated using mancozeb (0.3%) for 30 mins and stored in a well-ventilated place till planting (Shil et al., 2018).

2.1 Experiment setup

This study was conducted as a pot experiment in two different environments as the treatments: T1- Open field conditions, and T2: Greenhouse conditions. Ten pots (35 cm diameter and 40 cm height) were grown as replicates in each treatment under each condition. The pots were filled with soil (Topsoil: compost: sand 1:1:1) before planting. The 35–45 g healthy rhizomes were planted in plots. Basal fertilizer was added according to the Department of Export Agriculture (DEA, 2012) recommendations (TSP 100 kg/ha and compost 20 MT/ha), and pots were watered adequately at the planting. Top dressing (Urea and Muriate of Potash) was applied twice after 45 days and 90 days after rhizome establishment, at the rate of 65 kg/ha and 100 kg/ha, respectively according to the DEA (2012) recommendation.

2.2 Data collection

The Temperature (T) and relative humidity (RH) of the two conditions were measured using a hydrometer at 12.00 pm (mid day), and the monthly average was taken (Table 1).

Table 1: Average monthly temperature and relative humidity recorded at the field and the greenhouse conditions

Month	T _{in} (°C)	T _{out} (°C)	RH _{in} (%)	RH _{out} (%)
February-2021	39.14	31.29	65.59	66.58
March-2021	38.61	31.45	66.05	66.50
April-2021	38.60	30.95	66.06	66.19
May-2021	38.17	30.81	66.67	67.43
June-2021	38.20	30.87	66.84	66.13
July-2021	38.43	31.87	65.84	65.95
August-2021	38.63	31.77	66.10	66.45
September-2021	39.15	31.79	65.91	66.33
October-2021	38.37	31.83	66.04	65.98
November-2021	38.01	31.58	65.91	66.25
December-2021	37.67	31.50	65.97	66.25
January-2022	36.98	31.64	66.00	66.38

T_{in}: Average temperature in the greenhouse, T_{out}: Average temperature in the open field, RH_{in}: Average relative humidity in the greenhouse, RH_{out}: Average relative humidity in the open field

2.3 Agronomic data collection

At the maturity stage, ten months after planting, measurements were taken for plant height (cm), number of leaves, number of tillers, leaf blade length (cm), leaf petiole length (cm), and leaf width (cm) at the widest point of the leaf. Leaf blade length (cm), leaf petiole length (cm), and leaf width (cm) were measured on the fully expanded third leaf from the base of the turmeric plant (Ronya et al., 2020). Plant height was measured from the base of the plant (soil surface) to the tip of the tallest leaf which was fully expanded. Yield data was collected by harvesting the crop when the leaves had dried naturally, 11 months after establishment (Sagor et al., 2021). The fresh yield per plant (g per plant), number of mother rhizomes, number of primary fingers, number of secondary fingers per plant and canopy biomass per plant were recorded as yield parameters.

2.4 Data analysis

The collected data were analyzed using an independent sample t-test, and Pearson correlation analysis was conducted to investigate the relationship among different characters and yield in turmeric growth with SPSS statistical software (SPSS Inc., 2012).

3. Results and discussion

The average internal temperature of the greenhouse in the study period was 38.23 °C, with a range from 36.98 °C (January 2022) to 39.15 °C (February and September 2021). The average external temperature was 31.56 °C, ranging from 30.81 °C (May 2021) to 31.87 °C (July 2021). External temperatures were consistently lower than internal greenhouse temperatures (Table 1). The average internal relative humidity was 66.12%, with minor monthly fluctuations. Relative humidity values did not show substantial seasonal variation, with internal and external averages remaining steady near 66%.

The elevated internal temperatures in this study may have negatively impacted yield. Climate change, marked by rising temperatures, poses a serious threat to turmeric production, as excessive heat can suppress photosynthesis, reduce leaf area, and impair rhizome development (Sharangi et al., 2023; Retana et al., 2021). It has been concluded that *Curcuma* can be grown in a variety of tropical climates, including those with temperatures between 25°C and 30°C (Prasath et al., 2018). The maximum temperature exceeds 30°C at both conditions in the present study, reporting close to this optimal at open-field conditions. The reason would be that high temperatures (above 30°C) can accelerate leaf senescence, reduce chlorophyll content, and increase disease severity, such as leaf blotch (Mishra et al., 2021). Imbalanced temperatures reduce sprouting, rhizome growth, and photosynthetic efficiency (Liu and Heins, 1997; Begcy et al., 2018). Strategies like better temperature regulation and climate-resilient varieties are important to mitigate this impact.

The results reveal significant ($p < 0.05$) differences in turmeric growth and yield between open-field conditions and greenhouse conditions. Plants grown in greenhouse conditions had significantly greater plant height (100.62±8.95 cm) and wider leaves (10.95±1.07 cm) compared to open field conditions, which had a height of 89.31±11.79 cm and leaf width of 9.35±1.08 cm, indicating that the controlled greenhouse environment promoted shoot elongation and leaf expansion. However, open-field conditions exhibited advantages in several parameters, including a higher number of tillers (2.70±1.33 vs. 1.60±0.84), more mother rhizomes (2.70±1.34 vs. 1.60±0.84), and more secondary fingers (89.30±10.26 vs. 85.30±5.27), along with significantly greater fresh yield per plant (561.80±57.20 g vs. 429.50±65.09 g) and canopy biomass (274.30±73.31 g vs. 164.10±40.99 g). There were no significant differences between open-field conditions and greenhouse conditions in the number of leaves per plant (13.90±4.36 vs. 10.50±3.37), leaf blade length (42.46±15.98 cm vs. 38.28±1.53 cm), leaf petiole length (20.87±2.01 cm vs. 20.91±2.64 cm),

or the number of primary fingers (25.50 ± 4.03 vs. 24.20 ± 5.16). The results suggest that open-field conditions are more suitable for rhizome bulking, and overall yield, likely due to natural light and microclimatic factors whereas greenhouse conditions are more beneficial for enhancing vegetative growth such as plant height and leaf width. This finding is important to select growing conditions based on specific cultivation objectives, such as maximizing yield or promoting vegetative growth during nursery plant preparation.

Table 2: Mean values of the parameters and differences between the treatments as analyzed by independent sample t-test

Parameter	Treatment	
	Open field conditions	Greenhouse conditions
Plant height (cm)	89.31 ± 11.79^b	100.62 ± 8.95^a
Number of leaves	13.90 ± 4.36^a	10.50 ± 3.37^a
Number of tillers	2.70 ± 1.33^a	1.60 ± 0.84^b
Leaf blade length (cm)	42.46 ± 15.98^a	38.28 ± 1.53^a
Leaf width (cm)	9.35 ± 1.08^b	10.95 ± 1.07^a
Leaf petiole length (cm)	20.87 ± 2.01^a	20.91 ± 2.64^a
Number of mother rhizomes	2.70 ± 1.34^a	1.60 ± 0.84^b
Number of primary fingers	25.50 ± 4.03^a	24.20 ± 5.16^a
Number of secondary fingers	89.30 ± 10.26^a	85.30 ± 5.27^b
Fresh yield per plant	561.80 ± 57.20^a	429.50 ± 65.09^b
Canopy biomass	274.30 ± 73.31^a	164.10 ± 40.99^b

Data are means $\pm$ SD of three replications. Data with the same letter within each row for each treatment is not significantly different at the 5% level, based on the DMRT.

Low temperatures favor dry matter allocation to storage organs in root and tuber crops like turmeric and potatoes (Kandiannan et al., 2015). In many crops, temperature serves as a primary signal for leaf growth and elongation (Poiré et al., 2010; Matos et al., 2014), and moderately high temperatures reduce stem height and tiller number (Hemming et al., 2012; Dixon et al., 2019). High temperatures also enhance stem length and leaf numbers in basil plants (Al-Huqail et al., 2020). Increased temperatures accelerate development but decrease leaf area and fresh mass yield (Frąszczak and Knaflewski, 2009). This is due to elevated temperatures negatively impact chlorophyll content, Photosystem II (PSII) repair systems, and Rubisco activase activity, affecting photosynthesis and overall plant growth (Chen et al., 2020).

Under open-field conditions, the number of secondary fingers showed the strongest positive correlation with yield ($r=0.594$), indicating that secondary finger development significantly contributes to yield in open-field environments (Table 3). The number of tillers and the number of mother rhizomes also had moderately positive correlations with yield ($r=0.467$ for both), suggesting their importance in enhancing rhizome production. Interestingly, the number of leaves per plant exhibited a moderate positive correlation with yield ($r=0.442$), whereas plant height, leaf blade length, and leaf width displayed weak or negligible correlations ($r=-0.006$, -0.219 and -0.001 , respectively), implying that these traits are less influential on yield under open-field conditions (Table 3).

In greenhouse conditions, plant height demonstrated a strong positive correlation with yield ($r=0.813$, $p<0.01$), indicating that taller plants are more likely to produce higher yields in controlled environments. However, other parameters, such as leaves per plant ($r=0.492$), number of tillers ($r=0.040$), and number of mother rhizomes ($r=0.040$), showed weaker or negligible correlations with yield, suggesting that their impact is less pronounced in greenhouse conditions. Negative correlations were observed for number of secondary fingers ($r=-0.110$), leaf width ($r=-0.118$), and leaf blade length ($r=-0.041$), indicating these traits might have a minor or inverse relationship with yield under controlled environments (Table 3).

Table 3: Pearson correlations among different characters and yield in turmeric growth in open field conditions (T1) and greenhouse conditions (T2)

Treatment	PH	LVS	NT	LBL	LW	LPL	NMR	NPF	NSF
Open field conditions	-0.006	0.442	0.467	-0.219	-0.001	0.115	0.467	0.157	0.594
Green house conditions	0.813**	0.492	0.040	-0.041	-0.118	0.055	0.040	0.030	-0.110

** Correlation is significant at the 0.01 level (2-tailed)

PH: Plant height, LVS: Number of leaves per plant, NT: Number of tillers per plant, LW: Leaf width, LPL: Leaf petiole length, NMR: Number of mother rhizomes per plant, NPF: Number of primary fingers per plant, NSF: Number of secondary fingers per plant, FYP: Fresh yield per plant

Temperature-induced changes in growth parameters strongly influence crop yield. For instance, increased temperatures accelerate leaf senescence in crops reducing assimilate translocation and fruit weight (Li et al., 2015). In turmeric, yield improves with reduced maximum temperature, bright sunshine hours, evaporation during the bulking stage, relative humidity, and rainfall (Davis et al., 2024). Excessively high temperatures disrupt storing photosynthetic products due to reduced sink capacity and impaired biosynthesis of storage materials (Chen et al., 2016; Ribeiro et al., 2020). Optimal temperature ranges, such as 20–30°C, promote growth and yield, as observed in parsley, dill, and basil, depending on species-specific requirements (Frąszczak and Knaflowski, 2009; Putievsky, 1983). Balancing temperature with other environmental factors, such as temperature and humidity, is thus critical for maximizing yield potential.

Although a formal factorial ANOVA cannot be applied to statistically separate the individual or interactive effects of temperature and relative humidity due to the limited treatment structure, the observed biological patterns provide valuable insight. Under greenhouse conditions, where higher temperatures and slightly lower relative humidity prevailed, plant height increased; however, this did not translate into a proportional improvement in vegetative or reproductive growth. Most notably, fresh yield and associated reproductive traits were negatively affected. These trends suggest a combined (interactive) effect of elevated temperature and reduced humidity in suppressing reproductive development and overall yield.

4. Conclusion

The experiment demonstrated that temperature and relative humidity significantly affects various growth parameters and yield components of turmeric except for the number of leaves, leaf blade length, leaf petiole length, and number of primary fingers. Higher temperatures in greenhouse conditions (36.98°C – 39.15°C) increased plant height (100.62 cm) and leaf width (10.95 cm), whereas open field conditions with moderate temperatures (31.45°C – 31.87°C) favoured a higher number of tillers (2.7), mother rhizomes (2.7), secondary fingers (89.3), canopy biomass (274.3 g plant⁻¹), and fresh yield (561.8 g plant⁻¹). No significant correlations were observed between the traits and yield under open field conditions, whereas a significant positive correlation was identified ($r=0.813$, $\alpha=0.01$) for plant height under greenhouse conditions. Open field conditions generally outperformed greenhouse conditions for most traits, particularly in fresh yield per plant, canopy biomass, number of tillers, and number of mother rhizomes. Greenhouse conditions only showed an advantage in plant height and leaf width. Elevated temperature coupled with moderately reduced relative humidity under greenhouse conditions enhanced plant height but adversely affected reproductive development and yield performance. This suggests that while greenhouse conditions may support certain traits, open-field cultivation appears to be more effective for overall turmeric productivity and biomass accumulation.

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ICSD 056

**ENHANCING THE DURABILITY OF FINGER- JOINTED PINE (*Pinus caribaea*)
WOOD TO MITIGATE CLIMATE CHANGE****C. K. Muthumala^{1*}, K. K. I. U. ArunaKumara², De Silva Sudhira³, L. A. G. Alwis⁴**¹ Research, Development and Training Division, State Timber Corporation, Sri Lanka² Department of Crop Science, Faculty of Agriculture, University of Ruhuna, Sri Lanka³ Department of Civil and Environmental Engineering, Faculty of Engineering,
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Abstract: Wood is a renewable natural resource which can effectively reduce climate change. Wood processing operations generate enormous amount of wood residues which has the potential of lessening the effect of climate change. Human induced climate change is one of the most critical issues facing society in the 21st century. Increased use of forests and wood products, while not replacing the need to reduce greenhouse gas emissions at source, does make an important contribution towards tackling the problem of climate change. Storing CO₂ in wood could therefore be considered as an effective means of mitigating climate change. *Pinus caribaea* is the most common type of fast-growing softwood tree species grown in Sri Lanka, the total area planted exceeded 16,000 ha in 1870s. Microbial discolorations are more commonly encountered and among these the discoloration caused by blue stain fungi are the most prevalent. Blue stain always occurs on sapwood and most often in softwoods, hence pinewood should be preserved by Boron chemicals as soon as it is cut down and when it is converted into swan wood. Thus preservation of Pine wood is caused to enhance the durability of wood. Finger joint is a sustainable technique for minimizing the waste timber planks in timber industry. Major objective of this study is to evaluate of the impact on Borax-boric acid treatment for finger-jointed specimens. In present study, Pine sawn timber planks were treated by Boron impregnation plant and prepared finger-jointed specimens for testing of the effect of tensile strength. According to the results, average tensile strength values of untreated finger-jointed Pine specimens are higher than the recommended minimum requirement of tensile strength value ($\geq 10 \text{ N/mm}^2$) after seven days. Thus, it can be recommended that Boron treated finger-jointed timber planks with 19mm long fingers can be effectively used in industrial applications with enhancing the durability of Pine wood and to withstand climate change risk.

Keywords: Boron; Finger joint; Impregnation; Tensile strength; Waste

1. Introduction

Wood is one of the most important renewable natural resources available to man. The unique physical characteristics associated with different timber species and the engineering properties exhibited by wood have confirmed its suitability as a constructional material for a range of end uses. The strength properties of solid wood and the natural durability of certain species of timber have provided man with a material which has performed many functions including use as a building material for shelter and other constructions a means for transport on land and water and also in the air, a material for fabricating weapons, tools and utensils, furniture, as well as providing a source of extractive for industrials, domestics and pharmaceutical purposes. In addition wood is the basic raw material in the paper making industry, is used in the textile industry and is also used in the manufacture of wood composites and panel products (Youngs, 1989). Timber was man's first structural material and today is as important as ever for this purpose, it is likely, too through difficult to prove conclusively, that timber is used for a greater number of products than any other material (Brazier, 1987).

Trees sequester carbon during their life, pulling carbon dioxide (CO₂) from the atmosphere and storing it in their mass. For every kilogram of wood grown, 1.5 kg of CO₂ is removed from the atmosphere (ASCE, 2010). Storing CO₂ in wood could therefore be considered as an effective means of mitigating climate change, though wood also releases CO₂ when they used as fuels (Philippe, 2013).

Table 1. CO₂ released and stored by various building material during their construction

Material		Carbon released (kg/m ³)	Carbon stored (kg/m ³)
Rough sawn timber		15	250
Steel		5320	0
Concrete		120	0
Aluminum		22000	0

Source; Ferguson *et al*, 1996

Table 1 shows that timber material (rough sawn timber) is a best environmentally friendly construction material. Timber stores up to 15 times the amount of CO₂ released during its manufacture whereas Aluminium and Steel store negligible amounts. When comparing the various heat sources: wood, coal, fuel oil, gas or electricity, with a view to climatic impacts, the pertinent characteristic is the emission factor, which is the amount of carbon (or carbon dioxide) emitted per unit of released energy. Substitution of wood for fossil fuels does not reduce emissions of carbon dioxide because the emission factor of wood shows a higher value than that of other fuels in common use. Thus, giving the primacy to carbon sequestration is vital to increase the carbon stock in forests, wood products or in some kind of long-term wood storage (Philippe, 2013). Wood residues like saw dust, trimmings and edgings are typically viewed as a burdensome disposal problem (FAO, 1990). However, the material has a potential to become a usable resource (Bernad, 2014).

Wood waste defined as “saw dust, timber off-cuts, wooden crates, wooden packaging, wooden pallets, wood shavings and similar materials” (NSWEPA, 1997). The NSW Department of Environment and Climate Change defined wood wastes as “waste referring to the end-of-life products, failed products, off-cuts, shavings and sawdust from all timber products (NSWWB, 2000). Four types of wood wastes are usually generated within the furniture manufacturing companies as the result of the technological process: solid wood offcuts, engineered wood offcuts, sawdust and shavings (Daian & Ozasrka, 2009).

Off-cut wood is currently one of the wastes dumped by sawmills and as they failed to fully utilize the wood supply. Waste sawn timber material of furniture factory and short length of sawn timber are also big problem in timber industry in Sri Lanka. However, some of this wasted wood is already being used to fuel

kiln dried boiler. To further suggest ways to minimize the waste, by applying a jointing system, this utilizes the finger joint technique. This technology ensures maximum utilization of the timber thus minimizing the pressure on forest resources (Muthumala et al, 2019).

Finger joints are explained as interlocking end joint formed by machining a number of similar tapered symmetrical fingers in the ends of timber members using finger joint cutters and then connected together by bonding material (BS EN, 15497). Finger joint is a sustainable, eco-friendly and economically valuable concept for furniture industry. It ensures the sustainable utilization of small wood cut pieces which removed as waste (Sandika et al, 2017).

Atmospheric corrosion is a natural ageing process that causes damage to wood, logically relates to the presence of direct solar radiation, rainfall and more significant changes in climate. Wood in suitable environmental conditions can be attacked by bacteria, fungi, algae, insects, marine borers and some other biological pests.

The presence of wood-damaging agents has to be limited by using suitable designs with the aim to reduce contact of wood with rain and other sources of water, to reduce the creation of water condensate and to reduce the impact of ultraviolet light and fire. Chemical protection of wood is performed with preservatives, that is mainly with fungicides, toxic and insecticides, fire retardants and UV protective finishes that are applied on the wood's surface and also into its depth. The chemical protection of wood is performed with chemical protective agents called "wood preservatives". Fungicides for wood protection are classified into two groups; Organic and inorganic, according to their chemical structure (Reinprecht, 2016).

Boron (B^{3+}) in the form of boric acid (H_3BO_3), sodium tetraborate (borax, $Na_2B_4O_7 \cdot 10H_2O$) and sodium octaborate is normally used in aqueous solutions (Lin & Furuno, 2001). Borax and boric acid mixture was mixed with water (23 kg of borax and 15 kg of boric acid mixed in 1000 l of water) and used in the impregnation plant of the State Timber Corporation as an indoor preservative to preserve sawn timber.

Pine (*Pinus caribaea*) is the major softwood species grown in Sri Lanka used as furniture and construction works. Pine is an important source of raw material for sawmills, veneer plants, and paper mills (Gomes et al, 2004). Planting tropical Pines, an exotic to the island, commenced on a large scale in the early 1970s in the Up-Country Zone and Wet Zone lowlands. Plantations of Caribbean pine reached a total extent of 14,083 ha (inventoried extent. Planting of pines by the Forest department had ceased by the mid-1990s, and therefore stands in young age classes are now not available (Forest department, 2009).

Softwood timber species are easily deteriorated by wood destroying agents. Thus preservation of Pine wood is caused to enhance the durability of wood. Major objective of this study is to evaluate of the impact on Borax-boric acid treatment for finger-jointed specimens.

2. Methodology

Samples were cut from defects free, Seasoned (Moisture content 10-12 %) timber planks of Pine logs from the State Timber Corporation (STC), Galle, Sri Lanka to calculate tensile properties. Sawn timber planks were treated by Boron impregnation plant of STC in Boossa was used for this study (Figure 1). Borax and boric acid mixture were mixed with water (23 kg of borax and 15 kg of boric acid mixed in 100 l of water.



Figure 1: Impregnation plant –STC Boossa

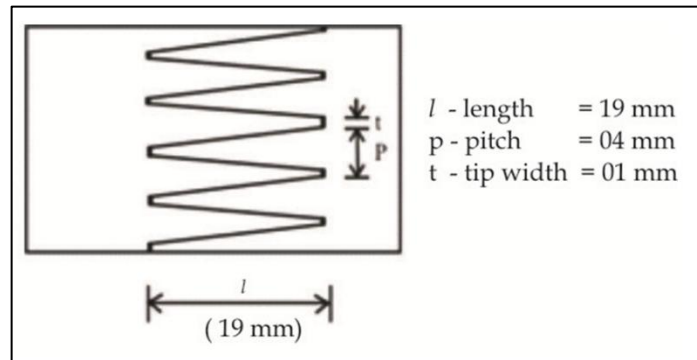


Figure 2: Geometric parameters of Finger joint

All the samples were made in finger joint factory in State Timber Corporation, Galle, Sri Lanka. Specimens with 19 mm finger joint length were prepared with 12 % moisture content. Treatment has been tested with an 8 % borax and boric acid equivalent solution of boric acid and borax in the ratio of 1: 1.5 in a commercial treatment plant at Boossa Timber Complex in the State Timber Corporation (Vindhya et al, 2024). Geometric parameters are shown in Figure 2. Schematic diagram of the experimental set-up is shown in Figure 3. The testing was done under both laboratory and manufactory conditions according to the regulations of the standard on BS EN 15497:2014 and BS 373:1957. Universal Testing Machine (UTM-100) which was made in Australia was used for testing (Figure 3). Polyvinyl acetate (PVAc), thermoplastic glue type was used as bonding material which belongs to D3 glue type (BS EN 204:2001) based on the previous studies (Muthumala et al, 2018). Assembling pressure 6 MPa were used in this study. Finger-jointed samples were prepared from defects free sawn wood, and dimensions of the sample and experimental setup is shown in Figure 4. Nine finger-jointed wood samples without Boron treatment, were cut from the Pine wood planks and used as the controls.

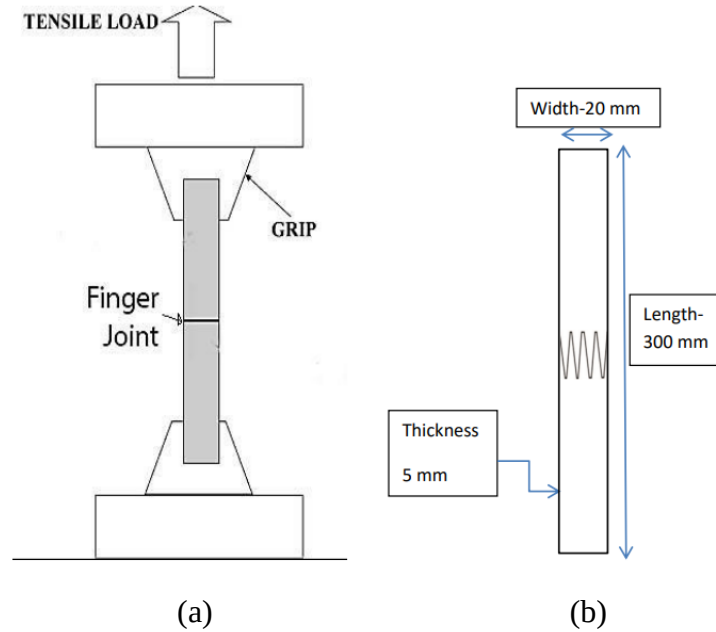


Figure 3: The Experimental set-up (a) and Dimensions of the sample (b) prepared for tension test.



Figure 4: UTM Machine (UTM-100PC-Australia) and Loading setup

The density values were calculated using following formulae. Dry weight of the timber samples were taken by placing in 105⁰C oven for 48 hours. (BS EN 373:1957)

$$\text{Density} = \frac{\text{Weight of oven dry wood (kg)}}{\text{Volume of wood (m}^3\text{)}} \quad (1)$$

Determination of basic density was done based on the green volume and oven-dry weight using a water displacement method. Polyvinyl acetate (PVA, P-SWR) adhesive was used for making finger joint samples (Muthumala, 2019). Sawn timber planks which were placed in seven days in normal room temperature conditioned showed good structural performance compared to hot and wet conditioned (Vivek et al, 2016).

Tensile strength was calculated using the equation 2.

$$\text{Tensile Strength} = \frac{\text{Maximum load (N)}}{\text{Area of cross-section of test length (mm}^2\text{)}} \quad (2)$$

3. Results and Discussion

Impact on Borax-boric acid treatment for finger-jointed specimens was investigated using nine untreated finger-jointed Pine specimens and 9 treated finger-jointed Pine specimens. Average density value of pine specimens varies between 625-650 kgm⁻³.

Table 2. T-test results of Boron treated specimens and untreated specimens

	No. of Specimens	Mean	Standard Deviation	Standard Error Mean
Pine without treatment	9	35.46	9.23	3.1
Pine with treatment	9	12.96	4.72	1.6

T-Value = 6.51 P-Value = 0.000 DF = 11

Average tensile strength values of boron treated Pine was 35.46 (N/mm²) and untreated Pine was 12.96 (N/mm²). According to two sample T-test results (Table 2), T value=6.51, P = 0.000.

Hence, strength value of boron treated finger-jointed specimens was lower than untreated finger-jointed specimens.

All the finger-jointed specimens showed higher strength values than DIN/EN 204-D3 test .With regard to DIN/EN 204-D3 test, Rosenheim, (2006) revealed that the minimum requirement of tensile strength value should be ≥ 10 N/mm² after seven days under dry conditions(EN 204, 2001). As revealed by the present study, all the tensile strength values of finger-jointed specimens bonded with SWR-D3 glue comply this value as all the tensile strength values are higher than ≥ 10 N/mm² . Mean Carbon stock (t ha⁻¹) of Pine monoculture forest plantations of Sri Lanka is 130.19 t ha⁻¹. Comparing of this value with Teak monoculture forest plantations, Teak shows the mean Carbon stock as 42.7 t ha⁻¹ (De Costa et al, 2012). Therefore use of short length sawn timber pieces for finger-jointed furniture production could contribute to Carbon storage. Flexural properties and compression properties of Pine wood and other local timber species were tested and published in previous studies (Muthumala et. al 2020a, 2020b, 2021a, 2021c, 2022a, 2022b, 2022c, 2024).

4. Conclusion

With regard to impact of borax-boric acid wood preservatives, the results confirmed that the average strength value of boron treated finger-jointed specimens was lower than untreated finger-jointed specimens. But average tensile strength values of untreated finger-jointed Pine specimens are higher than the recommended minimum requirement of tensile strength value (≥ 10 N/mm²) after seven days. Thus, it can be recommended that Boron treated finger-jointed timber planks with 19mm long fingers can be effectively used in industrial applications with enhancing the durability of Pine wood and to withstand climate change impact.

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ADOPTION OF SOILLESS CULTIVATION IN URBAN SRI LANKA: PUBLIC PERCEPTION, BARRIERS, AND OPPORTUNITIES

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Abstract: To address the food insecurity and malnutrition in Sri Lanka, urban agriculture has to evolve. Some techniques of soilless cultivation such as hydroponics or aeroponics or aquaponics provide sustainable solutions to enhance urban food production in such limited spaces. These methods have difficulty securing public adoption but fit the needs of urban environments. In this study we assess the socio economic, cultural and educational factors in shaping public perception of sustainable urban agriculture, identify the hindrances to the practice of sustainable urban agriculture, and offer practical recommendations to promote sustainable urban agriculture in Sri Lanka. A systematic review was performed, using PRISMA protocol, of 52 peer reviewed articles and reports (2004–2024) to analyze awareness, influence factors and adoption challenges under soilless cultivation. Moderate public awareness is found in key findings influenced by education and information access, while barriers including high costs and limited technical knowledge were found. Adoption in terms of founding of new links and restructuring of existing ones is critically driven by educational campaigns and policy incentives, the study finds, with a comparison made to trends in Sri Lanka and other countries in the world. Targeted awareness campaigns, subsidies to begin the setup and integration of soilless farming into urban planning and educational curricula, are some of the actionable recommendations made. For future research, long term impacts, cost benefit analyses, and scalable models for the integration of soilless system into urban food networks should be developed. For Sri Lanka to develop resilient and sustainable urban agriculture, there will be a need to address these gaps.

Keywords: Adoption Barriers; Educational Initiatives; Public Awareness; Soilless Cultivation; Sustainable Farming; Urban Agriculture

1.Introduction

FAO reports indicate that 60% of the world's hungry are women, and malnutrition contributes to the deaths of almost 5 million children under five each year (Mc Carthy et al., 2018). Food insecurity is typically measured by the prevalence of undernourishment, which refers to the percentage of individuals within a population who do not have access to sufficient food to meet their daily minimum dietary energy needs over the course of a year. Other forms of malnutrition are also considered as part of the broader concept of food insecurity. In 2021, it is estimated that between 691 to 783 million individuals worldwide experienced food insecurity (Iannotti et al., 2025). Food insecurity is more common in less developed countries than in developed countries (Mc Carthy et al., 2018). Urbanization can contribute to the emergence of slums, presenting a substantial challenge to food security across various aspects. This is because a significant portion of urban populations primarily rely on purchasing food and allocate a considerable portion of their income towards meeting their food needs (Li et al., 2013). Urban agricultural production encounters several obstacles, including difficulties in accessing key agricultural inputs such as land, fertilizers and water, operating within a polluted environment, and mitigating adverse environmental effects (De Bon et al., 2010). Soilless cultivation is considered a highly viable and suitable method for urban agriculture due to its ability to overcome challenges related to limited space, soil quality, and environmental concerns in urban settings. Soilless cultivation encompasses various techniques for growing plants without traditional soil as a rooting medium (Tzortzakis et al., 2020). Soil is the primary growth medium for plants, offering essential elements such as anchorage, nutrients, air, and water necessary for successful plant development. However, various soil types can present challenges to plant growth, including issues like inappropriate pH levels, soil compaction, poor drainage, erosion-induced degradation, and the presence of harmful organisms. Conventional open-field cultivation methods require significant resources like space, irrigation, technical equipment, and are subject to weather conditions. In urban areas or regions with limited arable land or unfavorable geographical conditions, soil-based cultivation may be constrained. The negative effects of conventional agriculture extend beyond crop growth conditions and encompass significant impacts on natural ecosystems. These include excessive and inefficient water usage, extensive land requirements, heavy fertilizer application, soil degradation, and loss of biodiversity (Fussy and Papenbrock, 2022).

1.1 Types of Soilless Systems

Conventional agriculture often involves substantial irrigation using freshwater and fertilizer inputs, resulting in relatively low yields. In contrast, hydroponics, aeroponics, and aquaponics are innovative agricultural systems that utilize nutrient solutions, sometimes in combination with inert substrates, instead of traditional soil-based methods for plant nutrition (Fussy and Papenbrock, 2022).

Soilless culture systems can be categorized into three main types: substrate culture, also known as solid support or aggregate system, which utilizes materials like gravel or agricultural perlite; solution culture, commonly referred to as hydroponic systems; and aeroponic systems. A solid support system in agriculture differs from pure solution culture by utilizing materials such as gravel to provide physical support for plants while retaining mineral nutrients and water. An aggregate system, on the other hand, involves cultivating crops in a solid medium, either inert or non-inert, instead of traditional soil. The selection of a solid support medium is based on factors such as the specific plant species being grown, the medium's capacity to hold water and air, and its drainage properties. This method allows for tailored cultivation practices that optimize plant growth and nutrient uptake in a controlled environment. Hydroponic systems, a form of soilless cultivation, can be classified as open (where the nutrient solution is not reused) or closed (where surplus solution is recovered, replenished, and recycled). Among the different hydroponic systems, the Nutrient Film Technique (NFT) is the most widely used. In NFT, a closed system, nutrients are continuously circulated, allowing plant roots to directly access the nutrient solution. This system requires close monitoring and frequent adjustments, including pH and nutrient testing, to ensure optimal plant growth. Aeroponics represents an advanced iteration of hydroponic systems, utilizing innovative technology to deliver nutrient solutions to plant roots in a fog-like spray. In this method, plants are secured in holes within

Styrofoam panels, with their roots suspended in the air beneath the panel. The panels form a sealed enclosure, and nutrient solution is applied as a fine mist to the roots. Misting is typically conducted for brief intervals every 2-3 minutes to maintain root moisture and ensure aeration of the nutrient solution. This approach allows plants to access nutrients and water from a film surrounding their root systems (Ghangal, 2017).

Figure 1 illustrates the impact of extension and research activities on growers' adoption of the soilless culture production system. The left pie chart shows that after being informed about the technology, 62% of growers expressed willingness to adopt it, while 6% declined and 32% did not answer. The right pie chart indicates that actual adoption was 51%, with 39% not adopting and 10% not responding. This highlights a positive influence of awareness programs but also reveals a gap between interest and actual adoption, likely due to high initial costs and a shortage of skilled labor (Charles, 2013).

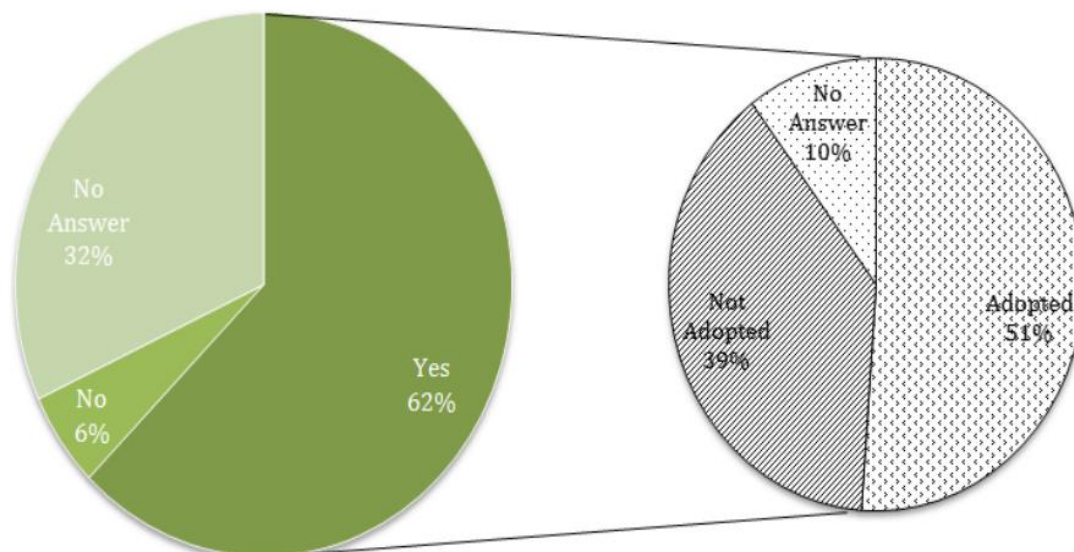


Figure 1: Growers' willingness to adopt the soilless culture production system after learning about the technology (left), and actual adoption rates (right). (Charles, 2013)

It is indeed possible to cultivate a wide range of crops such as cereals, vegetables, fruits, fodder crops, flowers, spices, and medicinal plants in hydroponic greenhouses. This method offers controlled environments that can support the growth of various types of plants without the need for soil. Numerous experimental studies demonstrate that leafy vegetables such as lettuce, spinach, parsley, celery, and Atriplex can be cultivated with relative ease and success using hydroponic systems. Hydroponic products often exhibit superior quality in terms of taste and nutrient composition compared to those grown through conventional soil-based cultivation methods (Fussy and Papenbrock, 2022). Soilless agriculture systems are ideal for urban settings because of their lightweight, modular design and precise control capabilities, allowing for optimal plant growth in constrained areas. In Sri Lanka, the uptake of these techniques in urban areas depends heavily on public perception and awareness, which play a crucial role in determining acceptance and implementation. The objective of this research is to explore the socio-economic, cultural, and educational factors that impact public attitudes and uptake of soilless cultivation practices in urban environments. The study seeks to identify the primary obstacles and difficulties that impede the acceptance and utilization of soilless cultivation methods in cities, and to offer practical suggestions for stakeholders such as policymakers, urban planners, and educators to promote greater awareness and adoption of sustainable farming approaches.

2. Methodology

2.1 Systematic Review Framework

The methodology for this review adheres to the PRISMA 2020 guidelines, ensuring a structured and transparent approach to the systematic review of literature concerning public perception, barriers, and opportunities for adopting soilless cultivation in urban Sri Lanka. This systematic review encompasses four distinct stages: Identification, Screening, Eligibility, and Inclusion (Page et al., 2021). This structured framework is instrumental in minimizing bias and enhancing the reproducibility of the findings, as emphasized in previous literature addressing the effectiveness of systematic reviews (Moher et al., 2015).

1.2 Data Sources and Search Strategy

The data sources for this review comprise well-regarded academic databases, including Web of Science, Scopus, ScienceDirect, Google Scholar, and SpringerLink. The search strategy utilized Boolean operators: ("soilless cultivation" OR "hydroponics" OR "aquaponics") AND ("urban agriculture" OR "sustainability") AND ("public perception" OR "adoption challenges"). The search was restricted to 44 studies published from 2010 to 2024, ensuring a focused analysis on recent developments and trends in the adoption of soilless cultivation in urban settings (Munn et al., 2018).

2.3 Inclusion and Exclusion Criteria

Inclusion criteria were set to encompass studies that specifically addressed peer-reviewed sources related to soilless cultivation, public perception, adoption challenges, and socioeconomic or environmental impacts. Conversely, exclusion criteria were established to filter out studies centered on traditional soil-based agriculture, those published in languages other than English, non-peer-reviewed sources, and research employing non-reproducible methodologies (Sulaiman et al., 2023). This careful selection helps maintain the findings' integrity and ensures relevance to current discussions on the adoption of soilless cultivation in urban Sri Lanka.

2.4 Study Selection Process

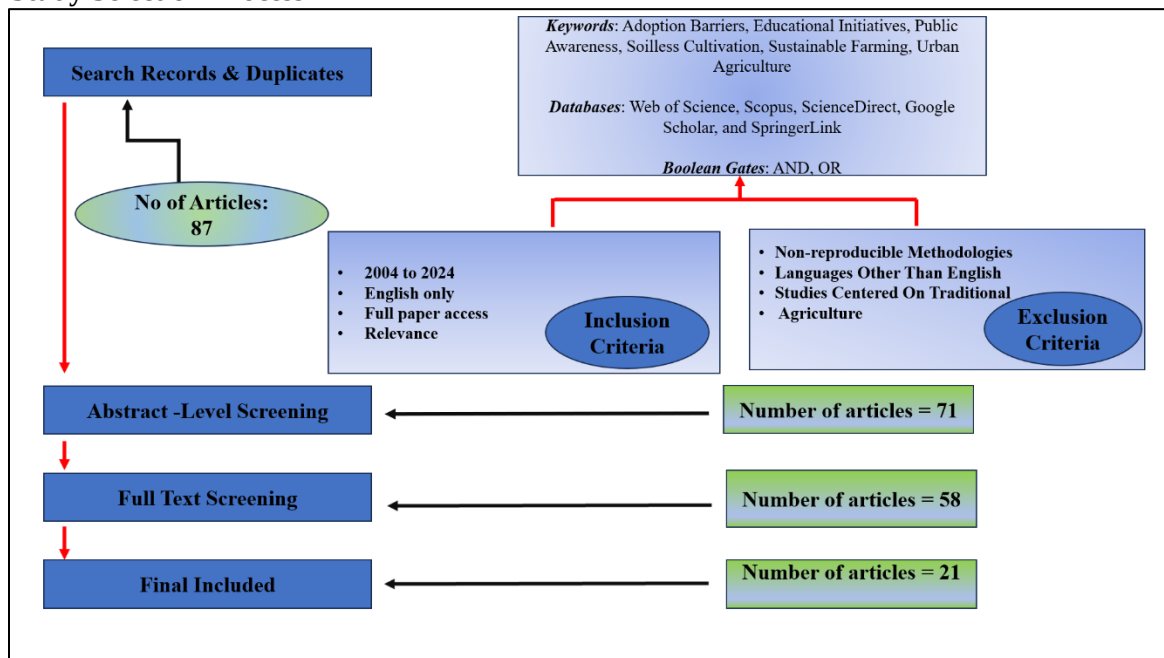


Figure 2: PRISMA Flow Diagram

The study selection process followed the PRISMA Flow Diagram (Figure 2) approach, consisting of three key stages: title and abstract screening, full-text review, and final inclusion. A dual-review methodology was employed, where two independent researchers evaluated the studies at each stage to minimize bias and ensure the reliability of the selection process. This systematic approach enhances transparency and facilitates the replication of the review process in future studies.

2.5 Data Extraction & Synthesis

Data extraction focused on variables critical to understanding the scope and impact of soilless cultivation in urban Sri Lanka. Variables included study context, methodology used, public perception, adoption barriers, and findings related to socioeconomic and environmental impacts. The synthesis of this data utilized a narrative approach to identify thematic trends across the literature, serving as a foundation for understanding the multifaceted benefits and challenges of soilless cultivation in urban settings. To mitigate the limitations associated with reliance on secondary data, the exclusion of non-English studies, and variability in methodologies, a cross-validation approach was applied, ensuring consistency and reliability in the interpretation of findings across diverse sources (Plener et al., 2022).

3. Results and Discussion

3.1 Socio-economic Factors

The economic feasibility and potential benefits serve as a powerful motivation for growers to adopt new technologies (Steve Hatfield-Dodds, 2007). Hydroponic production systems generally demonstrate strong economic feasibility, primarily due to their high yields, resulting in increased income, and their enhanced water productivity (Jensen, 1999). The adoption of vertical hydroponic lettuce cultivation presents a financially viable agricultural model, offering considerable profit potential under controlled conditions, while simultaneously enhancing food security and promoting sustainability within urban environments (Gumisiriza et al., 2022). Consumers are increasingly inclined to purchase fresh, cost-effective, locally grown products. Soilless cultivation underscores the significance of adopting innovative technologies to produce high-quality products at reduced prices. Protected agriculture, along with techniques like hydroponic systems, offers an effective solution by enabling the production of high-quality vegetable crops at a lower cost of production. While the initial investment may be higher compared to traditional soil-based systems, savings on operational costs, particularly in water usage, will help lower the overall expenses. Approximately 42 percent of farm owners directly distribute their products to the market (Charles, 2013).

Due to rapid urbanization and industrialization, land cultivation is increasingly facing significant challenges. In developing nations, there is frequently a limited understanding of conventional agricultural practices, coupled with inadequate dissemination of existing technological advancements (Hussain et al., 2014). The scarcity of available land for agricultural cultivation presents a growing challenge, which can be effectively addressed through the implementation of soilless cultivation techniques (Mir et al., 2022). The primary obstacles affecting the rate of adoption among growers are the high initial costs and the shortage of skilled labor. Cost-efficient hydroponic technologies that enhance automation are essential for reducing labor and operational expenses, thereby improving overall market accessibility and sustainability (Fussy and Papenbrock, 2022).

3.2 Cultural Factors

Sustainable urban food production has gained increasing attention in both professional and academic fields in recent years (Specht et al., 2014). Engagement in farming by urban households can enhance access to healthier and more nutritious diets. Among various agricultural techniques, soilless cultivation is considered the most effective method for urban dwellers, as it enables efficient food production in limited spaces while promoting the growth of nutrient-dense crops. Soilless gardening is increasingly recognized as a vital activity, with many considering farming as a key source of employment in the future. Hydroponic gardening, in particular, offers significant environmental benefits while providing a diverse range of fresh

vegetables for the daily nutrition of underserved populations. These systems serve a dual purpose: enhancing local food security and creating new sources of income. As a result, beneficiaries experience reduced food costs, improved dietary diversity, and the opportunity to generate income by selling surplus produce in local markets. Additionally, children benefit from improved access to fresh fruits and vegetables. These advantages contribute to the growing adoption of soilless cultivation methods by urban dwellers, fostering sustainable, efficient, and resilient food production systems (Orsini et al., 2013).

The sustainability of anthropogenic systems, particularly urban farming in buildings, hinges on the social acceptance of such practices. Social acceptance is a complex, multidimensional concept that cannot be fully captured by a single definition. It encompasses perceptions of the risks and benefits associated with urban farming, socio-economic characteristics of users, and their trust and beliefs. Key factors influencing acceptance include stakeholders' socio-demographic characteristics, such as age, gender, education, and financial status. Additionally, the degree of social distance to agriculture plays a crucial role. This includes the frequency and nature of interactions between residents and farmers, the sharing of values (e.g., a passion for plant cultivation), and residents' knowledge and awareness of agricultural practices and contexts. Enhanced knowledge of agriculture and a deeper awareness of the agricultural context are key factors that promote greater social acceptance of urban farming practices (“The Vertical Farm: Scientific Advances and Technological Developments - Google Books,” n.d.)

3.3 Educational Factors

Growers are likely to show interest in transitioning to soilless cultivation methods; however, they will need additional support and education to facilitate a successful shift. Understanding the logistics of transportation and shipping is crucial for adopting soilless substrates. Participants highlighted that the reduced weight of these systems, along with the associated shipping advantages, provides a compelling reason to adopt soilless cultivation. The participants' comprehension of these logistical benefits is essential for successfully transitioning to this innovative method (Fields et al., 2023). The technical assistance center offers educational support, agricultural inputs, and oversees commercial relationships. Its sustainability is secured through a percentage of the revenue generated from vegetable sales. Additionally, the center provides training to students from local agricultural schools, enhancing their practical knowledge and skills (Orsini et al., 2009).

3.4 Barriers

The primary challenge lies in the cost of adoption; the initial capital required for the implementation of advanced technologies, including AI-based monitoring systems, precision farming practices, novel materials, and alternative substrates, can be excessively burdensome for small-scale farmers. This financial constraint poses a significant risk of widening the technological gap within the agricultural sector, potentially restricting access to these innovations to only those with substantial financial resources, thereby disadvantaging smaller-scale operations (Fuentes-Peñailillo et al., 2024a). Another significant challenge is the technical complexity; operating and maintaining advanced systems generally requires specialized knowledge and training, creating a considerable barrier for farmers who may lack the necessary technological skills (Karunathilake et al., 2023). The effectiveness of these technologies can be affected by a range of external factors, including climate, geographic location, and market demand, which may restrict their applicability in certain contexts or environments (Barnes et al., n.d.).

Concerns over the regulations governing their activities were often voiced by growers. They stated that having a thorough awareness of the legal requirements and suggested best practices would be great. The sheer volume of potential credentials offered by different authorities and organizations frequently left them feeling overpowered. Among the growers, controlling the growth of algae was a recurring problem. Implementing standardized techniques to manage algae development was deemed a big issue for many of them, and they voiced a great need for this. Growers overwhelmingly expressed a critical need for concise

and standardized training programs to ensure employee awareness and adherence to food safety best practices. Furthermore, they stressed the importance of accessible, preferably free, training resources to guarantee that all growers, including small-scale operations, can obtain the necessary knowledge to comply with food safety regulation (Hamilton et al., 2023).

Soilless cultivation demands advanced infrastructure, including skilled labor and the implementation of automated, computerized systems for the management of artificial lighting, water, nutrients, and pesticide applications. Introducing such technologies to farmers in substandard conditions presents a significant challenge (Gebereegziher, 2023). Simultaneous measurement of macro and microelements, along with extended signal stability, represent key challenges in nutrient management for growers engaged in soilless cultivation systems (Sambo et al., 2019). Ongoing maintenance is crucial for sustaining the functionality of the system and mitigating the risk of potential malfunctions or failures. Regular and proper maintenance practices are essential to ensure the system operates optimally over time. Soilless cultivation systems require energy input to sustain ideal conditions such as temperature, humidity, and nutrient supply, which can lead to higher operational costs (Bihari et al., 2023).

3.5 Opportunities

One of the most significant advancements in modern agriculture is the integration of computer technology, particularly in controlled environment agriculture. Technologies such as crop monitoring systems and mobile applications enable farmers to make informed decisions regarding the timing, location, and methods for planting, irrigation, fertilization, and pest control. These innovations offer numerous advantages, including enhanced control over production processes, improved and more sustainable yields, and greater adaptability to fluctuations in weather conditions. Sensor technologies, for instance, facilitate continuous monitoring and real-time identification of crops, often incorporating automated regulatory systems for more precise management. The use of automation is poised to further increase production efficiency, allowing for more effective oversight of agricultural operations at the individual plant level with reduced labor input. Additionally, advancements in agricultural engineering are expanding farming capabilities into new methods, locations, and environments. Among these innovations, hydroponics has emerged as one of the fastest-growing sectors, potentially shaping the future of global food production (Fussy and Papenbrock, 2022). The future will undoubtedly demand the development of novel, well-designed growing media, alongside innovative technologies capable of recovering nutrients from organic waste streams. The integration of bio-sensing technologies in the root zone environment will enable more cost-effective, precise, and real-time decision-making, offering significant improvements over current methods. Continued research is essential to identify and further develop sustainable materials, technologies, and strategies that minimize energy consumption and production costs, while also reducing transportation distances (“Advances in horticultural soilless culture - Google Books,” n.d.). Automation is progressively gaining importance in soilless vegetable production, providing transformative advantages while presenting challenges that warrant thorough evaluation. Technologies such as automated nutrient delivery systems, climate control, and robotic harvesting have the potential to revolutionize the industry by improving efficiency, lowering labor costs, and boosting crop productivity. These automated systems enable precise regulation of various environmental parameters, including nutrient levels, humidity, and temperature, creating optimized growing conditions that enhance the quality of the produce. In soilless vegetable production, the integration of precision farming techniques into hydroponic and substrate-based systems is an emerging trend with significant potential. Precision agriculture serves as a valuable tool to enhance both production and quality, while simultaneously minimizing resource usage and reducing environmental impact (Fuentes-Peñailillo et al., 2024b).

4. Conclusion

This review examines the key factors influencing the public perception and adoption of soilless cultivation in urban Sri Lanka. It focuses on socio-economic, cultural, and educational aspects that affect acceptance. A systematic approach was employed to analyze these influences. Key barriers identified include high initial costs, technical complexity, and lack of standardized training, while opportunities such as automation, precision farming, and policy incentives provide a clear pathway for future expansion. The study emphasizes that targeted educational initiatives, integration into urban planning, and governmental support are crucial for widespread adoption. Soilless cultivation, through hydroponics, aeroponics, and aquaponics, offers scalable, resource-efficient solutions to food insecurity and malnutrition, particularly in urban environments. For Sri Lanka to achieve resilient, sustainable urban agriculture, bridging gaps in knowledge, infrastructure, and regulation is essential. Future research should focus on long-term impacts and the development of context-specific, cost-effective models.

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IMPACT OF NATURAL AGING ON THE PHYSICOCHEMICAL PROPERTIES OF WHEAT FLOUR DURING SHORT-TERM STORAGE: IMPLICATIONS FOR BAKING QUALITY AND SHELF-LIFE OPTIMIZATION

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Abstract: Wheat flour, a cornerstone of global food systems, undergoes significant physicochemical changes during storage, which can profoundly influence its baking performance and shelf-life. This study investigates the effects of natural aging on the physicochemical properties of wheat flour over a six-week short-term storage period under controlled conditions (22°C, 45–55% relative humidity). Two commercially available wheat flour samples (S1 and S2) with identical extraction levels, alongside a blended sample (S3, mixed in a 3:2 ratio), were analyzed weekly for key parameters, including moisture content, protein content, gluten content, crude fat, crude fiber, ash, carbohydrates, maltose, pH, water absorption capacity (WAC), water holding capacity (WHC), and oil holding capacity (OHC). Results revealed significant ($P < 0.05$) changes in moisture, protein, gluten, crude fat, maltose, pH, WAC, WHC, and OHC, while ash, carbohydrate, and crude fiber contents remained stable. Notably, protein content decreased substantially (e.g., S1: 10.56% to 6.17%), and maltose content became undetectable after six weeks, indicating enzymatic degradation. These findings underscore the dynamic nature of wheat flour during storage and highlight the need for optimized storage practices to preserve functionality. This study provides valuable insights for food manufacturers and bakers aiming to enhance product quality and extend shelf-life, contributing to sustainable food systems.

Keywords: Natural aging; Physicochemical properties; Short-term storage; Baking quality; Gluten; Maltose

1. Introduction

The global wheat flour industry operates with the fundamental assumption that flour stored well retains uniform quality for extended periods. Mondal and Datta (2008) argued that there is no complete science backing this assumption, particularly in the context of short-term storage periods typical in commercial operations. Even though literature exhaustively documents long-term storage phenomena (>12 weeks), a key knowledge gap exists regarding physicochemical changes in the short-term storage stage (4–8 weeks) under controlled conditions. Current understanding of wheat flour aging comes primarily from studies investigating longer storage durations. Hrušková and Machová (2002) depicted extensive protein degradation during 16 weeks of storage, while Kurek et al. (2015) focused on trends of moisture migration over intervals of 20 weeks. These studies fail to address the actual real-time industrial environment in which flour is typically consumed within 6–8 weeks of milling. This temporal mismatch between study and industry represents a significant weakness in current knowledge.

The originality of this study is its rigorous investigation of short-term storage dynamics under controlled industrial conditions. Unlike previous studies that tend to examine a single parameter or ambient storage conditions, this study provides detailed analysis of eleven physicochemical parameters for six weeks of storage under real industrial conditions. Additionally, while most studies examine a single flour sample, this study examines two commercial flours and their industrial mixture, reflecting actual practice. The critical research gap bridged in this study is the assumption that flour quality remains unaltered during short-term storage. Zhou and Attard (2014) suggested that enzymatic activity continues in significant proportion during initial storage weeks, though to date there has been a lack of confirmation of this hypothesis. This study discredits existing paradigms with evidence that key quality parameters alter significantly within commercially relevant time frames. Building on previous research by Nguyen and Waskey (2018), who published preliminary evidence for short-term aging effects, this research further develops this understanding with quantification of the changes in individual protein, gluten, and maltose composition, as well as functional properties. Integration of the moisture-dependent functional properties (WAC, WHC, OHC) with compositional change provides new insights into flour behavior during storage.

The practical utility of this research is more than theoretical. Industrial baking operations require precise ingredient specifications, yet current storage practices may not adequately respond to temporal quality variation. Through development of evidence-based standards of storage, this research contributes to greater product consistency and reduced loss in industrial food chains. This study aimed to bridge this knowledge gap by systematically evaluating the effects of natural aging on the physicochemical properties of wheat flour during a six-week storage period. The specific objectives were threefold: (1) to assess changes in the proximate composition of wheat flour, including moisture, protein, gluten, fat, fiber, ash, and carbohydrates; (2) to evaluate alterations in functional properties, such as water absorption capacity (WAC), water holding capacity (WHC), and oil holding capacity (OHC); and (3) to analyze the correlation between moisture content, WAC, and WHC. By addressing these objectives, this research provides actionable insights for optimizing storage practices, enhancing baking performance, and reducing food waste, thereby contributing to sustainable food systems.

2. Materials and Methods

2.1. Sample Selection and Characterization

Two randomly selected commercially available wheat flour samples represented different milling operations in Sri Lanka's industrial flour milling industry. Samples were collected within 48 hours of milling to ensure similar baseline conditions. Sample S3 was prepared by blending S1 and S2 in a 3:2 ratio, which is common industrial blending practice to achieve maximum cost-performance ratio. The ratio was selected upon consultation of industry experts and is indicative of usual blending ratios used in Sri Lankan bakeries. Early characterization reported small but significant differences between samples: S1 contained $10.56 \pm 0.12\%$ protein, while S2 contained $10.23 \pm 0.15\%$ ($p < 0.05$). Gluten content was also different (S1:

8.36±0.18%, S2: 8.51±0.14%). These differences, while within commerce tolerance, provided opportunity to investigate how early flour characteristics influence aging patterns. Storage conditions were strictly controlled to simulate industrial conditions. The samples were stored in food-grade polyethylene bags (250g) at 22±1°C and 45–55% relative humidity in environmental chambers. These are conditions typical of normal industrial storage in the tropics and different from earlier research that utilized ambient conditions or very high temperatures. Six weeks was selected as experimental duration based on industry consultation that 80% industrial flour is utilized within six weeks. Sampling W1–W6 weekly provided sufficient resolution to track temporal changes and be practically feasible for overall analysis.

2.2. Experimental Design

The storage experiment spanned six weeks, with samples analyzed weekly (W1–W6) in triplicate. The physicochemical properties assessed included moisture content (oven drying and IR moisture analyzer methods), protein content (Kjeldahl method), gluten content (wet and dry gluten assays), crude fat (Soxhlet extraction), crude fiber (gravimetric method), ash (muffle furnace incineration), carbohydrate content (by difference), maltose content (HPLC with refractive index detection), pH, WAC, WHC, and OHC.

2.3. Analytical Methods

All the analysis was done by following standardized procedures to make it reproducible and accurate. Both oven drying (105°C, 4 hours) and infrared moisture analyzer (AOAC 925.10) were used to estimate moisture content. Kjeldahl method (AOAC 990.03) was utilized to estimate protein content, and gluten content was estimated with wet gluten extraction followed by drying (ICC Standard 106/2). Fat extraction of crude fat employed the Soxhlet method (AOAC 920.39), and maltose was determined by high-performance liquid chromatography with refractive index detection (LCHE/TM/SOP/097). Functional properties like water absorption capacity (WAC), water holding capacity (WHC), and oil holding capacity (OHC) were measured by standard method adapted for wheat flour analysis.

2.4 Statistical Analysis

Data were analyzed with analysis of variance (ANOVA) and analyzed using Minitab 19 software assistance. Tukey's pairwise test identified some differences among the means at $p < 0.05$ levels. Correlation studies were conducted to examine correlations between moisture content and functional properties utilizing Pearson correlation coefficients.

3. Results & Discussion

3.1. Proximate Composition Changes

The proximate composition of wheat flour exhibited varying degrees of change during storage (Table 1, 2 & 3).

Table 1: Summary of Proximate Composition Changes Over Six weeks

Parameter	Sample	W1	W6	P-Value
Moisture (%)	S1	13.5	13.1	<0.05
Protein (%)	S1	10.56	6.17	<0.05
Gluten (%)	S1	8.36	7.11	<0.05
Crude Fat (%)	S1	0.78	1.12	<0.05
Ash (%)	S1	0.52	0.51	>0.05
Carbohydrate (%)	S1	75.46	75.23	>0.05
Crude Fiber (%)	S1	0.45	0.44	>0.05

Table 2: Summary of Proximate Composition Changes Over Six Weeks of S2

Parameter	Sample	W1	W6	P-Value
Moisture (%)	S2	13.8	13.4	<0.05
Protein (%)	S2	10.23	7.34	<0.05
Gluten (%)	S2	8.51	7.7	<0.05
Crude Fat (%)	S2	0.86	1.33	<0.05
&Ash (%)	S2	0.55	0.54	>0.05
Carbohydrate (%)	S2	75.12	74.89	>0.05
Crude Fiber (%)	S2	0.47	0.46	>0.05

Table 3: Summary of Proximate Composition Changes Over Six

Parameter	Sample	W1	W6	P-Value
Moisture (%)	S3	13.6	13.3	<0.05
Protein (%)	S3	10.43	6.99	<0.05
Gluten (%)	S3	8.56	7.47	<0.05
Crude Fat (%)	S3	0.96	1.21	<0.05
Ash (%)	S3	0.53	0.52	>0.05
Carbohydrate (%)	S3	75.28	75.06	>0.05
Crude Fiber (%)	S3	0.46	0.45	>0.05

3.1 Protein and Gluten Degradation: Challenging Industry Assumptions

The most striking observation was the high and rapid protein degradation observed in all samples. Protein content decreased from 10.56% to 6.17% in S1, 10.23% to 7.34% in S2, and 10.43% to 6.99% in S3 within six weeks ($p < 0.05$). This represents a 41.5%, 28.3%, and 33.0% decrease respectively, far exceeding the 10–15% breakdown that would be expected in short-term storage. These results directly contradict the industry assumption that protein content remains stable during short-term storage. Hrušková and Machová (2002) reported similar degradation rates but over 16-week periods, suggesting that enzymatic activity during initial storage weeks is more intense than previously recognized. The differential degradation rates between samples ($S1 > S3 > S2$) indicate that initial flour characteristics significantly influence aging patterns.

Gluten level also reflected the same degradation pattern, 8.36% to 7.11% in S1, 8.51% to 7.70% in S2, and 8.56% to 7.47% in S3. Swan et al. (2017) assumed that gluten degradation would be primarily apparent under prolonged storage conditions, but this study demonstrates phenomenal changes within six weeks. The implication for bread baking quality is extensive as gluten strength has a direct correlation with dough handling attributes and final product volume.

3.2 Maltose Depletion: Major Implication for Fermentation

The most practically important observation was the complete depletion of maltose content by week 6 in all samples. Initial maltose levels of 0.74% (S1), 0.82% (S2), and 0.78% (S3) were no longer quantifiable ($LOD = 0.02\%$) at the end of week 6, suggesting complete enzymatic degradation.

This finding is contrary to current understanding of α -amylase activity during storage. Mondal and Datta (2008) discussed maltose's critical role in yeast fermentation and crust colouration, but reported that significant depletion occurred after months of storage. The more rapid loss of maltose found in this study suggests α -amylase remains highly active during the initial weeks of storage, potentially compromising baking performance within commercially important time frames.

The consequences for application are important. Maltose depletion directly affects fermentation rates, flavor development, and browning of crusts in baked foods. Large-scale industrial bakers that rely on uniform maltose content for their routine procedures of fermentation can experience substantial product variability with 6-week-aged flour, even under controlled laboratory conditions.

The pH of wheat flour decreased initially, followed by a rapid increase (Figure 4.10). For S1, pH dropped from 5.84 to 5.71 by W5, then rose to 5.77 by W6. Similar patterns were observed for S2 and S3, with significant ($P < 0.05$) changes likely due to organic acid production and subsequent neutralization (Kibar, 2015). The reason for PH increment can be the organic acid production due to fermentation.

3.3 Moisture-Dependent Functional Properties: Dynamic Interactions

Water absorption capacity (WAC) and water holding capacity (WHC) showed complex patterns of variation rather than linear declines. S1 showed initial WAC decrease (65.2% to 62.8% through W2), followed by recovery (66.1% through W4), and thereafter variation. This is contrary to previous reports of steady pattern decrease over long storage. The fluctuating patterns in moisture, WAC, and WHC reflect the complex interplay between environmental conditions and flour composition. Moisture migration, influenced by storage humidity, likely drove these fluctuations, affecting flour's hydration properties and, consequently, its baking performance (Kurek et al., 2015). The initial increase and subsequent decrease in OHC suggest dynamic changes in flour hydrophobicity, possibly linked to lipid oxidation and protein-lipid interactions (Johnson et al., 2019).

Correlation analysis revealed high positive correlation between moisture content and WAC ($r = 0.85$, $p < 0.05$) and moderate correlation with WHC ($r = 0.68$, $p < 0.05$). The correlation reveals that moisture migration under storage conditions affects functional properties to a large extent, a finding in contrast with the assumption of controlled storage efficacy.

Oil holding capacity improved significantly in all samples as well (S1: 53.26% to 60.22%, S2: 52.8% to 59.5%, S3: 53.1% to 59.8%). This increase, likely a result of lipid oxidation and protein-lipid interactions, indicates hydrophobicity of flour changes over storage. Johnson et al. (2019) suggested such change predominantly occurs over long-term storage, but in this study, significant changes within six weeks have been observed.

The increase in crude fat content, albeit slight, points to lipid oxidation, a process known to produce free fatty acids and reactive oxygen species, which can further degrade flour quality (Swan et al., 2017). Conversely, the stability of ash, carbohydrate, and crude fiber contents indicates that these components are less susceptible to short-term aging, providing a reliable baseline for nutritional labeling and product development.

3.4 Stable Parameters: Finding Consistent Quality Indicators

Ash, carbohydrate, and crude fiber contents were statistically the same upon storage ($p > 0.05$). These findings show that mineral composition and the complex carbohydrate scaffolds withstand the short-term influences of aging and provide stable parameters of quality estimation even in aged flour. Such stability is then contrasted with dynamic changes observed in levels of protein, gluten, and maltose. This difference lends experimental insight to quality control systems and suggests that ash content could be an acceptable stable reference point while protein and maltose must be tracked over time.

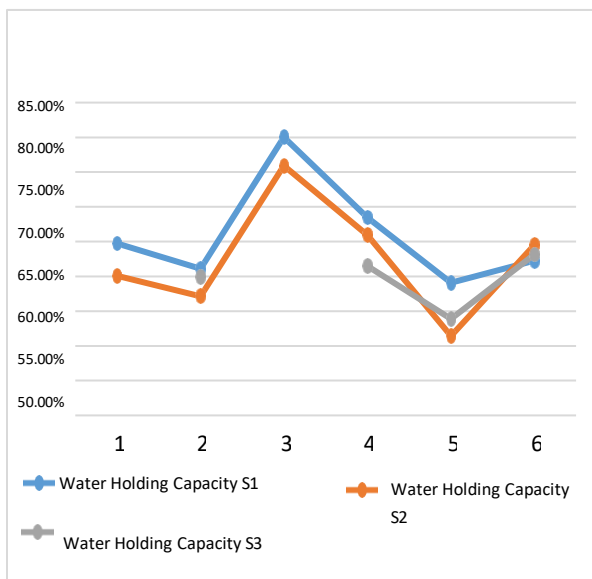


Figure 1: Water Holding Capacity Vs Time

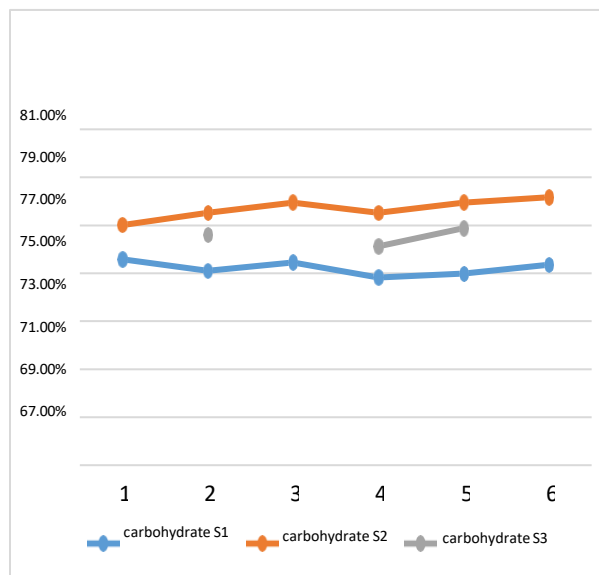


Figure 2: Carbohydrate Content Vs Time

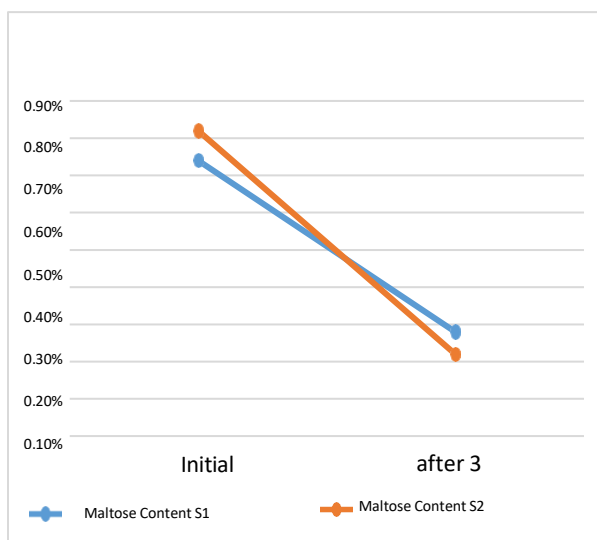


Figure 3: Maltose Content Vs Time

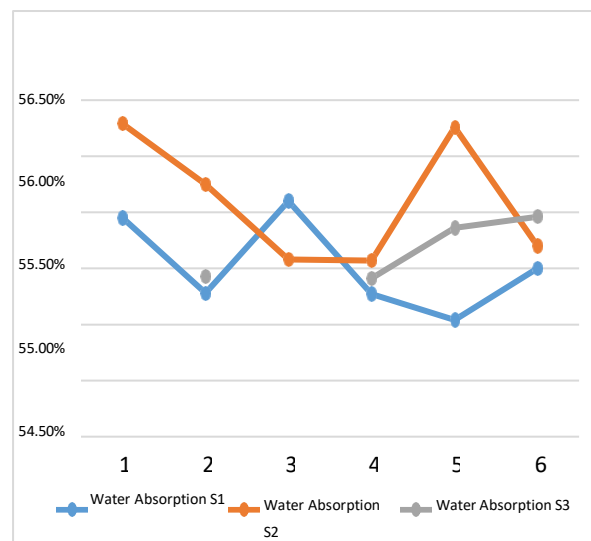


Figure 4: Water Absorption Capacity Vs Time

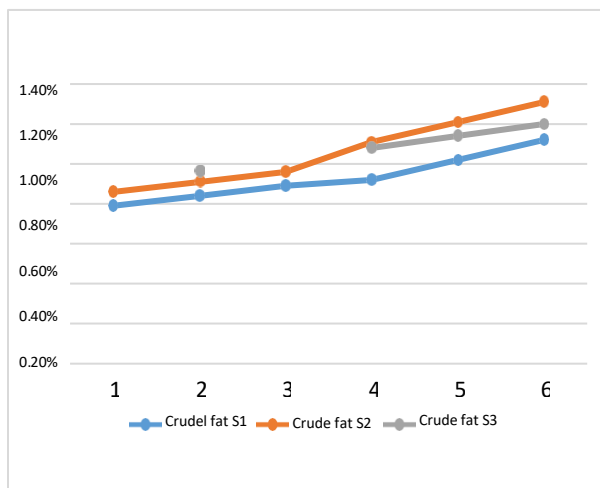


Figure 5: Crude Fat Content Vs Time

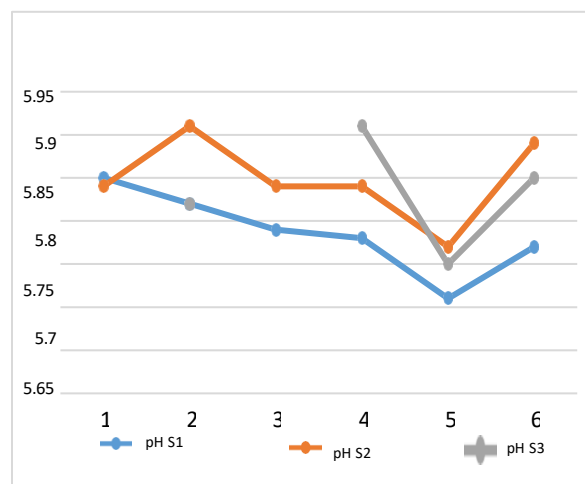


Figure 6: PH Vs Time

Table 4. Summary of Functional Property Changes Over Six Weeks

Parameter	Sample	W1	W6	P-Value
Water Absorption Capacity (WAC, %)	S1	65.2	64.8	<0.05
	S2	64.9	64.5	<0.05
	S3	65	64.7	<0.05
Water Holding Capacity (WHC, %)	S1	72.3	71.9	<0.05
	S2	72.1	71.7	<0.05
	S3	72.2	71.8	<0.05
Oil Holding Capacity (OHC, %)	S1	53.26	60.22	<0.05
	S2	52.8	59.5	<0.05
	S3	53.1	59.8	<0.05
Maltose Content (%)	S1	0.74	ND*	<0.05
	S2	0.82	ND*	<0.05
	S3	0.78	ND*	<0.05
pH	S1	5.84	5.77	<0.05
	S2	5.86	5.79	<0.05
	S3	5.85	5.78	<0.05

3.5 Industrial Operation Practical Implications

The findings reveal that existing industry norms may be short of accounting for quality differences over time. The fact that there is extensive protein degradation and complete depletion of maltose after six weeks means that storage procedures must be redesignated. Industrial bakers ought to consider the installation of time-based quality measuring systems rather than relying on initial specifications.

The differential aging patterns across samples show that flour sourcing practices must account for potential for aging. S1's more rapid protein degradation indicates that certain flour traits position products for premature aging, requiring alternative storage or usage protocols.

4.3. Comparison with Existing Literature

Compared to previous studies that predominantly focused on long-term flour storage, the current study has a more informative and time-scale-based assessment of how certain quality markers behave under short-term commercial storage. Hrušková and Machová (2002) and Kurek et al. (2015) had earlier pointed out significant changes in proteins and water under longer storage durations (12–20 weeks), but not shown the enhanced degradative trends as are now evident in eleven variables in this study. Our findings show that even at six weeks, there are staggering drops in protein, gluten, and maltose far sooner than recorded in long-term storage books. Moreover, functional considerations such as WAC, WHC, and OHC experienced dynamic changes hitherto unknown in short-term research. Crude fat content showed oxidative increases, while moisture, pH, and carbohydrate content fluctuated in manners that reflect environmental considerations more varied than static assumptions in earlier studies. In contrast to relative constancy in qualities like ash and crude fibre, as predicted by previous work, this study provides new knowledge by tracking compositional and hydration behaviour simultaneously under manufactured conditions. Thus, our contribution towards the current body of literature is multi-dimensional characterization of short-term flour ageing, revealing that significant functional and compositional deterioration already occurs far in advance of time scales typically investigated in previous work.

5. Conclusion

This study presents strong evidence that wheat flour undergoes radical physicochemical changes when stored for short durations of time under intended industrial conditions. The intense protein degradation (up to 41.5% loss), complete elimination of maltose, and dynamic functional property variation defy fundamental physiological industry assumptions about flour stability across typical storage times.

The significant contributions of the work are: (1) quantitative physicochemical analysis of eleven attributes over commercially relevant storage periods, (2) demonstration that major quality markers change substantially within six weeks, and (3) identification of differential patterns of aging in commercial flour samples and blends.

The findings call for qualitative revamping of industrial storage protocols and quality control mechanisms. Time-based quality assessment should be applied instead of fixed specifications, particularly for protein, gluten, and maltose content, as the findings suggest. More research needs to proceed to identify storage interventions that minimize loss in terms of quality and develop rapid analytical methods for real-time quality monitoring.

Acknowledgments

The authors gratefully acknowledge the support of Prof. M.A. Jagath Wansapala and Mrs. Shyama Rajapaksha for their invaluable guidance and encouragement. We also thank the staff of the Department of Food Science and Technology, University of Sri Jayewardenepura. This research was conducted as part of the B.Sc. Honours Degree program at the University of Sri Jayewardenepura.

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EMERGING TECHNOLOGIES FOR RESILIENT AGROECOSYSTEMS

SWOT ANALYSIS ON CIRCULAR ECONOMY PRACTICES IN FISHERIES SECTOR IN SRI LANKA; A CASE STUDY IN SOUTHERN COASTAL BELT OF SRI LANKA

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Abstract: The fisheries and aquaculture sector plays a vital role in Sri Lanka's economy and food security. The adoption of sustainable practices is crucial due to increasing pressure on marine ecosystems and resource inefficiencies. This study investigates the current trends and applications of circular economy (CE) principles in the fisheries sector and aquaculture industry in the Southern Coastal Belt of Sri Lanka. A survey analysis was conducted based on data collected from 54 fishermen across five major harbors, such as Mirissa, Hikkaduwa, Ambalangoda, Dondra and Kudawella. The findings reveal significant challenges in adopting CE practices, including high costs, lack of knowledge and limited infrastructure. While a very limited number of respondents consistently prioritized eco-friendly materials, most emphasized cost and availability over sustainability. Waste management remains a critical concern with improper disposal of wastewater, plastic and chemical residues posing environmental risks. Recycling and resource repurposing efforts, such as using fish offal for fertilizers and feed are limited by financial constraints and market access issues. Despite these challenges, the study identifies substantial opportunities such as improved recycling infrastructure, access to training and financial incentives to encourage sustainable practices. Respondents suggested the establishment of recycling centers, the development of new technologies and collaborative efforts to enhance resource recovery and minimize waste. This study highlights the urgent need for targeted interventions to facilitate the transition towards a circular economy in the fisheries and aquaculture sector. Those sectors can achieve significant environmental and economic benefits by addressing existing barriers and fostering awareness. Integrating CE principles into this industry will not only mitigate environmental impacts but also contribute to resilient coastal communities and sustainable economic growth in Sri Lanka.

Keywords: Circular Economy; Fisheries and Aquaculture sector; Recycling; Waste management

1. Introduction

The concept of the circular economy (CE) has gained considerable attention in recent years, especially in sectors such as agriculture, as a solution to the unsustainable patterns of resource use and waste generation. As the world faces growing environmental challenges, the traditional linear models of production and consumption—take, make, dispose—have proven to be unsustainable, leading to resource depletion and increased waste. The circular economy offers an alternative framework, focusing on the efficient use of resources, minimizing waste, and maximizing the recovery and recycling of materials, energy, and nutrients. By doing so, the circular economy significantly reduces environmental impacts and fosters long-term sustainability in industries like agriculture and fisheries (Fahimeh et al., 2024).

A circular economy is often seen as a strategy to reduce the environmental impact of human activities. By utilizing resources more efficiently and recovering them at the end of their lifecycle, circular systems result in less waste and fewer emissions compared to traditional systems (Chary et al., 2023). This concept has particular relevance for the fisheries sector, where sustainable practices are urgently needed due to increasing pressure on marine and freshwater ecosystems.

Circular economy principles have been extensively applied to the agri-food systems, including fisheries, to promote sustainability. Muscat et al. (2023) proposed five core principles for transitioning agri-food systems into a circular bio-economy: safeguarding the health of aquatic ecosystems, minimizing waste, optimizing the use of biomass (thus preventing competition between food, feed, and fuel), recycling by-products, and integrating renewable energy sources. These principles, while broadly applicable, are especially pertinent to the fisheries sector in Sri Lanka, where the over-exploitation of marine resources and environmental degradation pose significant challenges. The idea is that both products and production systems should be designed to reduce their environmental footprint across their lifecycle, aligning with sustainable circular economy goals.

Scientific evidence continues to grow regarding the negative effects of agriculture, including aquaculture, on natural resources and ecosystems. Food production, particularly in the context of fisheries and aquaculture, has been identified as a key driver of environmental change (Verreth et al., 2023). As global consumption of natural resources has risen due to rapid industrialization and economic growth, the need for sustainable practices, such as circular economy models, becomes more urgent (Wang et al., 2021). These models, when implemented in fisheries sector, can help mitigate the negative environmental impact of food production while supporting the sector's growth.

In recent years, several circular economy (CE) concepts have been explored in the context of modern fisheries and aquaculture sectors. These include waste management, nutrient and byproduct recycling, and the incorporation of novel CE-derived ingredients in feeds. Circular bioresource efficiency, which emphasizes smart resource utilization and the repurposing of waste, has also been shown to contribute significantly to stress-resilient fisheries and aquaculture (Lakra et al., 2022). These approaches not only improve sustainability but also offer economic benefits by creating new opportunities for resource reuse at the local level, thereby fostering resilient communities and economies.

However, while the potential benefits of adopting circular economy practices are clear, the fisheries sector in Sri Lanka faces several challenges in implementation. A study by Ekanayake and Galdolage (2024) identified key opportunities for the country's fisheries, such as improved technology, skilled human resources, post-harvest loss reduction, value addition, and diversification into aquaculture and mariculture. However, challenges remain, including limited access to finance, weak infrastructure, and governance issues. Overcoming these obstacles will be crucial for the sector to achieve sustainable growth, contribute to the country's economic development, and enhance the livelihoods of fishers and their communities.

Despite the potential for a successful transition to a circular economy in Sri Lanka's fisheries, there remains a significant gap in understanding how circular economy (CE) principles can be applied consistently across different sectors, leading to uneven implementation strategies (Shweta et al., 2021). Furthermore, micro-social entrepreneurs often face barriers such as regulatory compliance and limited access to resources, which hinder the widespread adoption of CE practices (Conlon et al., 2019). In addition, existing business models often fail to align with the principles of circular economy, making it necessary to rethink how firms operate and engage with stakeholders to adopt more sustainable practices (Antonella et al., 2020).

New methods focused on recycling waste from fisheries and aquaculture, transforming it into fish flesh, simultaneously reduce the environmental impacts. Das et al. (2022) emphasize that key factors such as simplicity, energy efficiency, and cost considerations play a critical role in achieving circularity and improving resource use within fisheries and aquaculture systems. Moreover, the implementation of circular bio-economy principles in Sri Lanka's fisheries sector could help address the pressing environmental and economic challenges while fostering long-term sustainability.

The need for a comprehensive assessment of circular economy practices in the fisheries sector in Sri Lanka, particularly in the southern coastal belt, is therefore essential. This study aims to conduct a SWOT analysis to identify the strengths, weaknesses, opportunities, and threats associated with the adoption of circular economy practices in the fisheries sector in this region. By examining these factors, the study will provide valuable insights into how Sri Lanka can enhance its fisheries sector's sustainability through circular economy principles, addressing the existing research gap and contributing to the broader discussion on circular economy applications in fisheries.

2. Materials and Methods

2.1 Study Area

Five harbors located in Southern coastline of Sri Lanka were selected namely, Mirissa, Hikkaduwa, Ambalangoda, Dondra and Kudawella.



Figure 1: 01: Mirissa 02: Hikkaduwa 03: Ambalangoda 04: Dondra and 05: Kudawella harbours

Harbours in Southern coastal belt Sri Lanka

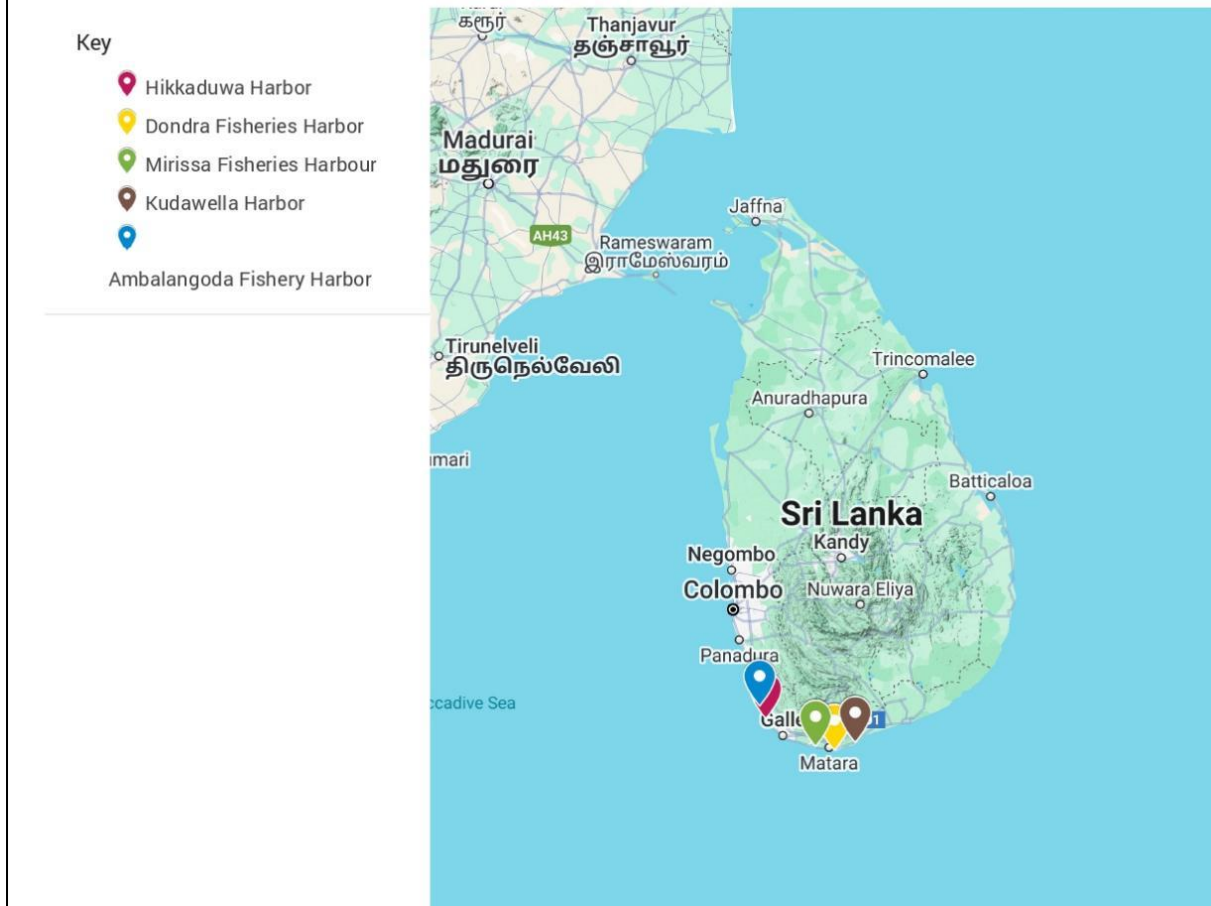


Figure 2: Harbours selected for the study from Southern coastal belt, Sri Lanka.

The Mirissa Fishery Harbor, located at 5° 56'55.05" N, 80° 27'1.54" E in the Weligama Bay of Sri Lanka's Southern Province (Figure 3). It is a key operational hub for the fisheries and aquaculture sector. Established in 1966, the harbor spans 2 hectares of land and 6.2 hectares of basin area, with a berthing capacity for 300 vessels. It features essential facilities such as fish auction areas, net mending spaces, boat lifting equipment and fuel and water supplies. It supports sustainable operations and aligns with circular economy practices. Its strategic location and infrastructure make it an ideal case study for exploring waste reduction, resource reuse and sustainable management in the Southern Coastal Belt.

The Hikkaduwa Fishery Harbor, situated at 6° 08'35.77" N, 80° 05'53.19" E, is located in the heart of Hikkaduwa. It is a popular tourist destination in Sri Lanka's Southern Province (Figure 4). Established in 2001, the harbor covers a land area of 1.35 hectares and a basin area of 4.5 hectares, with a berthing capacity for 250 vessels. Adjacent to the country's only marine sanctuary and famed for its coral reefs. This harbor serves as a hub for both fisheries and eco-tourism. Key facilities include a fish auction hall, net mending building, boat lifting services and a fuel station with a 36,000-liter storage

capacity. Its integration with tourism and sustainable fishing activities makes it a valuable location for circular economy initiatives in the Southern Coastal Belt.

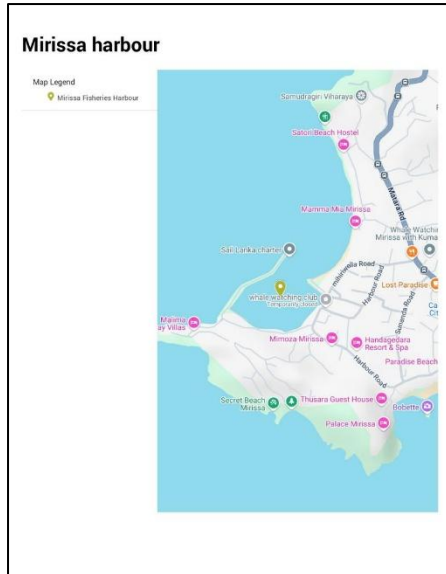


Figure 3:Location: Mirissa Fisheries Harbor



Figure 4:Location: Hikkaduwa Harbor Complex

The Kudawella Fishery Harbor, located at $50^{\circ} 58' 33.39''$ N, $800^{\circ} 44' 1.54''$ E, in the Hambantota District of Sri Lanka's Southern Province (Figure 5). It is one of the largest harbors managed by the Ceylon Fishery Harbours Corporation (CFHC). Commissioned in 1998, it spans a land area of 3.3 hectares and a basin area of 10.3 hectares, with a berthing capacity of 400 vessels. Proximity to the renowned Hummanaya Blow Hole adds eco-tourism value. Key facilities include an ice plant, fish auction hall, net mending building, and fuel supply services. Supporting infrastructure, such as water storage tanks (36,000 liters), a workshop and workers' quarters, strengthens the harbor's role in sustainable fisheries. Kudawella's robust infrastructure and strategic location make it ideal for implementing circular economy practices in Sri Lanka's fisheries sector.

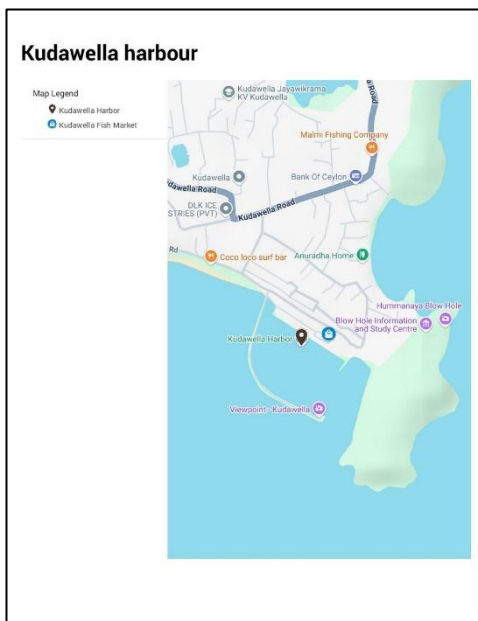


Figure 5:Location: Kudawella Harbor

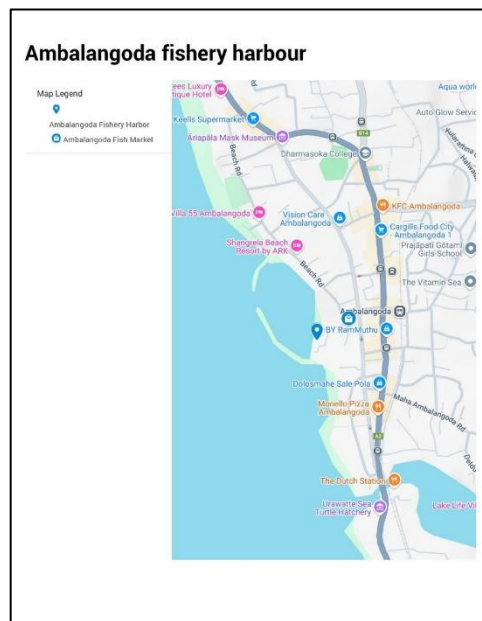


Figure 6:Location: Ambalangoda Fisheries Harbor

The Ambalangoda Fishery Harbor, located at 60° 14'7.86" N, 80° 03'2.07" E, in the Galle District of Sri Lanka's Southern Province (Figure 6). It was commissioned in 2010 as part of the ADB-funded Coastal Resource Management Project (CRMP). This natural harbor benefits from existing protection provided by a headland, a reef and an island. Spanning a land area of 3.67 hectares and a basin area of 5.3 hectares, it has a berthing capacity of 150 vessels and a dredging depth of 3.5 meters. Facilities include a cool room, auction hall, net mending area and fuel supply, supported by general amenities like water supply, a canteen and a radio room. Ambalangoda's strategic location and infrastructure make it a valuable site for advancing circular economy practices in the fisheries sector of Sri Lanka.

The Dondra Fishing Harbor, located at 5°55'15.52" N, 80°35'1.22" E in Southern Sri Lanka (Figure 7), is a key hub for fishing and maritime activities. Surrounded by scenic coastal views and rich marine biodiversity, the harbor supports both traditional fisheries and eco-tourism. Its proximity to the iconic Dondra Lighthouse enhances its appeal, offering panoramic ocean views and opportunities for observing marine ecosystems. The harbor also serves as a cultural site, reflecting the daily practices of the local fishing community. Dondra's blend of ecological and cultural significance makes it an essential location for studying sustainable fisheries management.

2.2 Data Collection and Analysis

The data for this study were collected through a primary survey conducted at the above-selected five major fishing harbors in the Southern coastal belt of Sri Lanka. A total of 54 fishermen who were available and willing to participate during field visits were surveyed using an orally administered questionnaire on circular economy practices in their sector.

The questionnaire explored the practices and challenges of implementing a circular economy in the fisheries and aquaculture sector in Sri Lanka's Southern Province. It covered key areas including eco-design, waste management, equipment refurbishment, and recycling. Respondents were asked about their approaches to selecting environmentally friendly materials, repurposing waste (such as fish offal, plastic waste, and wastewater), and extending the life of equipment. The survey also investigated obstacles to adopting circular practices, such as high costs, lack of knowledge, and limited availability

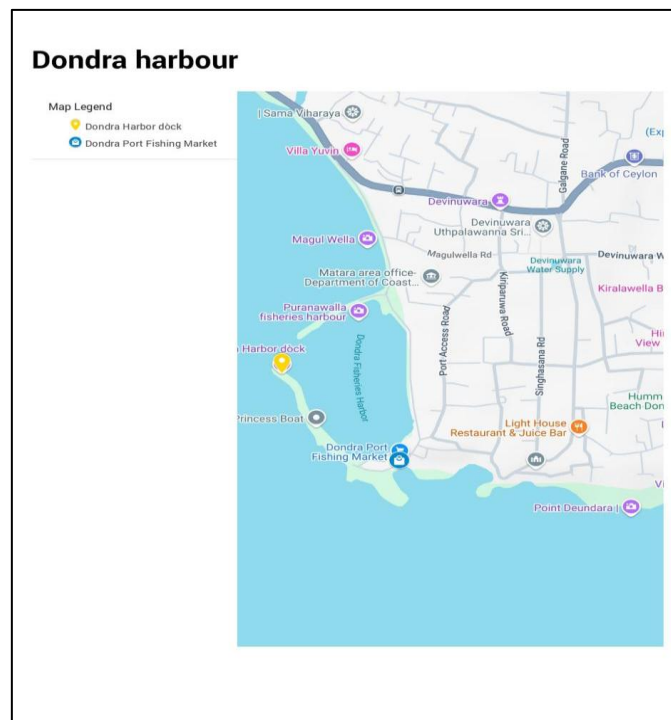


Figure7: Location: Dondra Harbor

of eco-friendly resources. It aimed to gather insights into current waste management practices, the potential for waste-to-resource conversion, and the feasibility of circular economy concepts in the region.

The survey responses were used to assess the current practices and challenges within the sector, contributing to a SWOT analysis of Circular Economy practices in the Southern coastal belt.

3. Results and Discussion

The selected harbours were Hikkaduwa, Mirissa, Ambalangoda, Dondra and Kudawella, and the survey was conducted between October 2 and October 24, 2024. The majority of responses were collected from Mirissa and Ambalangoda, representing prominent coastal areas with active fishing communities. Table 1 shows respondents from each harbours consider for this survey.

Table 1: Respondents from each harbour

Harbor	Number of Respondents
Hikkaduwa	6
Kudawella	10
Dondra	5
Ambalangoda	13
Mirissa	20
Total	54

The professional experience of the respondents varied significantly, offering a comprehensive view of perspectives across experience levels. Specifically, around:

20% had 1–5 years of experience,

25% had 5–10 years of experience,

35% had 10–15 years of experience, and

20% had more than 15 years or undisclosed levels of experience (noted as “>” in the dataset).

This diversity in geographical location and years of involvement in the fisheries sector ensures that the findings reflect a broad spectrum of information, from early-career participants to seasoned professionals.

Environmental considerations in equipment choices

When examining their preference for eco-friendly materials, only 3.7% respondents prioritized eco-friendly materials despite higher costs, while most respondents (77.8%) focused primarily on cost and durability while over the environmental impact of materials. This shows the tendency among fishery community to prioritize short-term economic benefits rather than focusing on sustainability which can be a long-term benefit. This highlights the need of awareness on material choices, sustainable living and long-term environmental impacts despite economical benefits.

Durability and re-usability of materials in operation

46.3% of respondents valued the durable materials conditionally (only if they are affordable and readily available). 24.1% respondents cited reduced costs and waste minimization as benefits of using durable materials. Conversely, 13% respondents do not prioritize durability at all as they have the idea that durable material are costly. The initial cost of durable material can be identified as a significant barrier despite their long-term benefits in resource conservation and waste reduction.

Modifications in fishing equipment to reduce environmental impact

About 53.7% of the respondents have made minor eco-conscious changes (e.g., reusing parts), while only 9.3% have already implemented significant changes to use less harmful materials to the environment. 25.9% respondents made no changes due to cost considerations. Lack of technical knowledge, proper idea on significant environmental harm and inadequate training are major barriers in modifying fishing equipment to reduce harmful environmental impacts.

Waste generation and management

In this section, the types of waste they generate in their operations, were categorized. 50% of respondents/their harbours or working sites generate mixed waste, including wastewater, fish waste, organic waste, plastic waste (nets, ropes, packaging), and chemical waste. Plastic waste and chemical waste are prominent, often posing environmental risks. Also, the ways they dispose their waste, was questioned (Table 2 and Figure 8).

Table 2: Waste Disposal Practices among Respondents (N = 54)

Type of Waste	Proper Disposal (%)	Improper Disposal (%)	Both Methods / Mixed (%)
Wastewater	46.3%	44.4%	9.3%
Fish and Organic Waste	46.3%	37.0%	16.7%
Plastic Waste	55.6%	24.1%	20.3%
Chemical Waste	24%	46.3%	29.7%*
Sludge	18.5% (used as fertilizer)	42.6% (no disposal method)	38.9% (other/unknown)

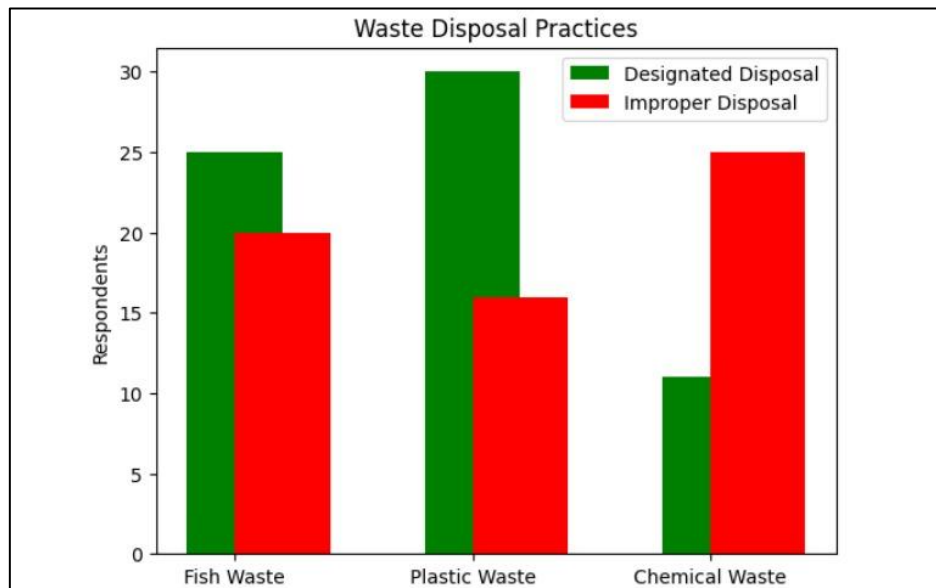


Figure 8: Waste disposal practices among respondents

For fish waste, designated disposal slightly exceeds improper disposal. In contrast, plastic waste shows a significantly higher number of respondents opting for designated disposal. However, for chemical waste, improper disposal surpasses designated disposal, highlighting a critical area for improvement.

Recycling and waste-to-resource practices

Under recycling efforts, 30% repurpose waste as fertilizer, while 38.9% of the respondents repurpose it as animal feed. They were questioned on how viable is the waste-to-resource idea in their current operations. Only 9.3% respondents find waste-to-resource approaches feasible without additional support while 50% respondents find financial constraints, 40.7% respondents find lack of knowledge or training and limited access to recycling programs or markets as the main barriers to recycling.

Maintenance and equipment longevity

Despite the barriers to CE and undesirable practices abundant in this field, a significant proportion of the respondents clean and store equipment properly after use which is a positive response in terms of CE implementing potential.

Table 3: Maintenance Practices for fisheries equipment (N = 54)

Equipment Type	Respondents Practicing Proper Maintenance (%)
Fishing nets	61.1%
Storage boxes	53.7%
Other equipment	59.3%

Minimal maintenance or not using specific practices are common for refrigerators. According to the results, table 3 shows 61.1% respondents repair equipment to reduce resource use, however, only 16.7% buy second-hand items, indicating low integration of reuse principals.

Barriers to adopting circular economy practices

The existing obstacles for adapting to circular economy practices were questioned and financial constraints were identified as the most concerning issue among the respondents indicating a 55.1% from total responses. It was also evident that a significant portion of respondents agreed that lack of technical support and technical knowledge is also a considerable obstacle (34.7%). Other than these knowledge and technical gaps, inaccessibility and being a time consuming process also have affected the adaptability to CE practices among this community (Figure 9).

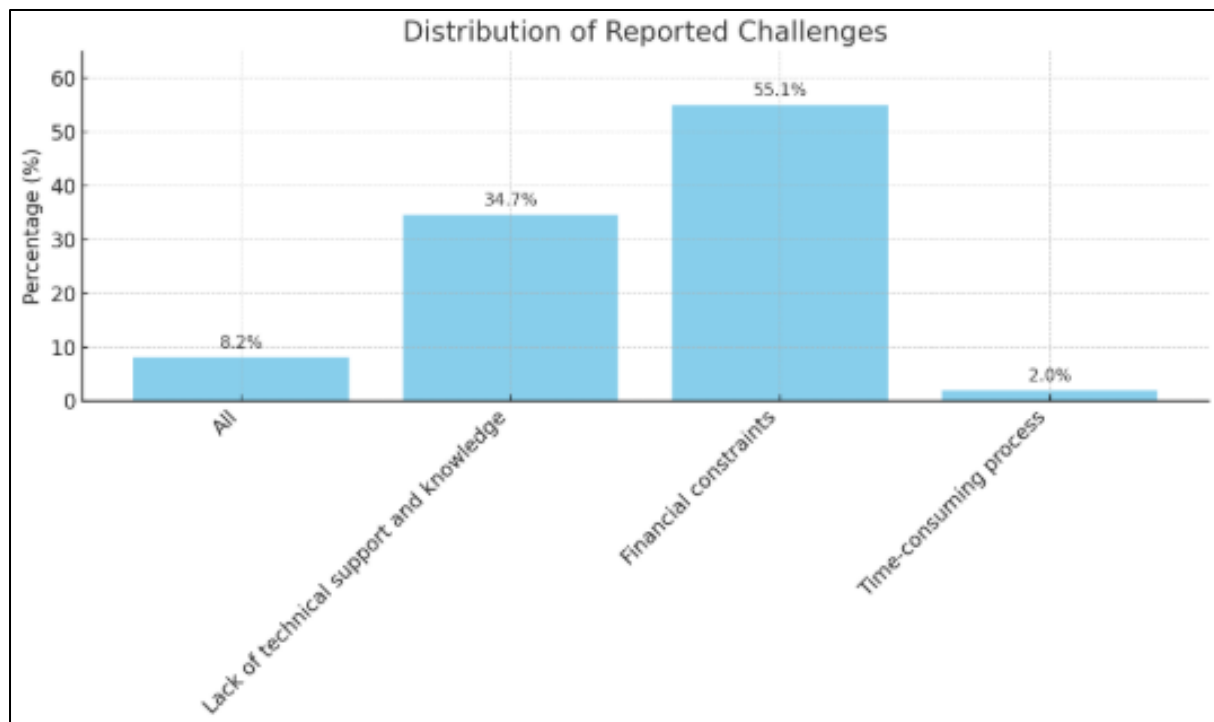


Figure 9: Existing barriers to recycling end-of-life products

There are some interventions suggested by respondents in this regard. 48.2% respondents suggested improving of establishing accessible recycling centers in coastal areas, 23.2% indicated the need of financial support, 17.9% suggested providing training on recycling methods and 10.7% suggested the need of access to new recycling technologies (Figure 10).

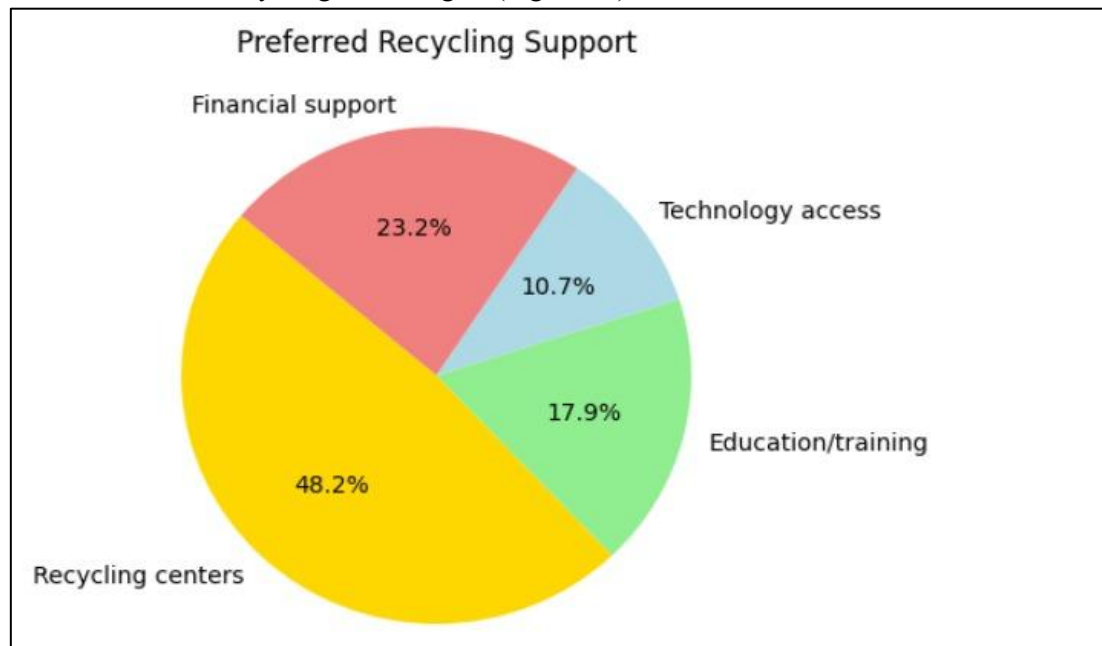


Figure 10: Preferred recycling support type by respondents

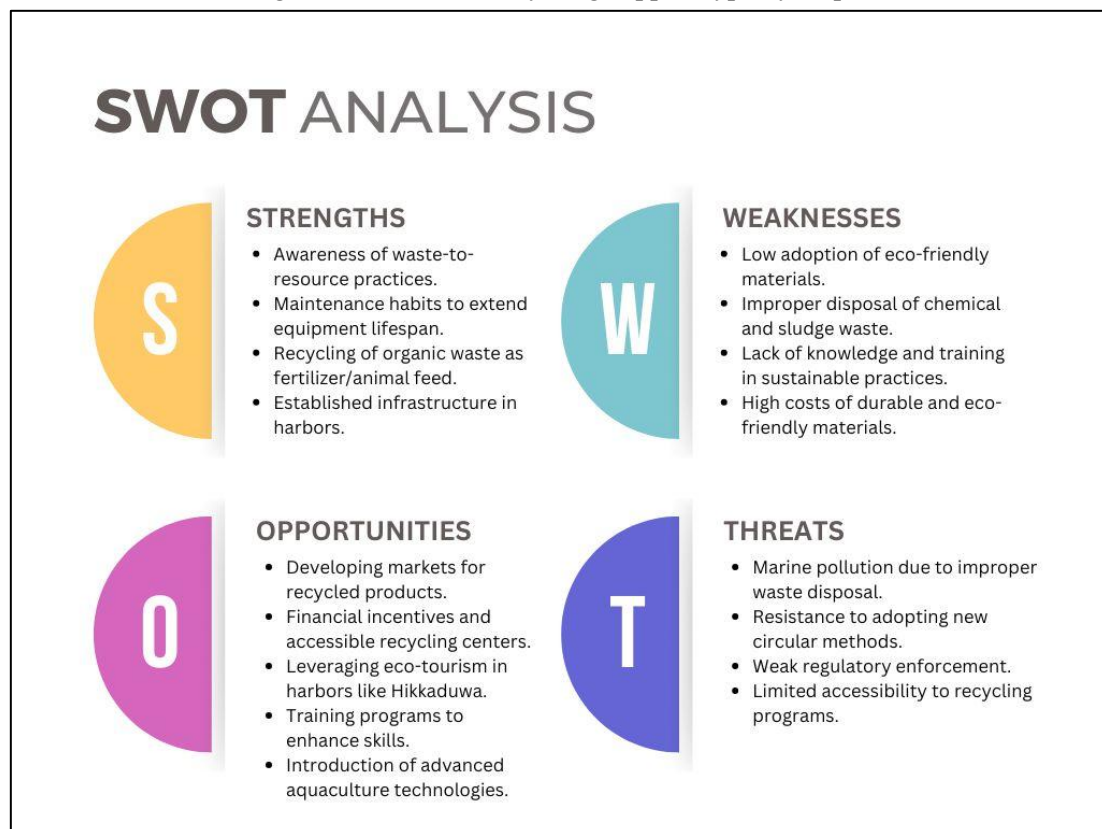


Figure 11: SWOT analysis summary

4. Conclusion

The findings of this study explain that while circular economy principles are conceptually understood to a certain level by fishing communities along Sri Lanka's Southern coastal belt, practical implementation is still remaining limited due to barriers including economic, technical, and infrastructural barriers. Choice of fishing equipment is mostly driven by cost and then availability and accessibility, with a least concern on environmental impact. This reflects the short-term economic mindset that overshadows sustainability goals, which is a common scenario when it comes to any other industry. However, positive signs still exist in this sector especially in the form of routine equipment maintenance and repair (which is not so common with other industries), indicating a foundational readiness for circular practices. Waste management of the sector yet remains inconsistent, especially for chemical and sludge waste which are often disposed improperly, posing serious environmental risks. Organic waste recycling methods, such as producing fertilizer or animal feed, shows promise but remains underutilized due to financial and knowledge constraints. Other solutions such as establishing biogas plants, and incentivizing the use of second-hand equipment and shared resources, can further reduce waste and help close the loop. Financial incentives, such as subsidies for adopting eco-friendly materials and recycling technologies, and building partnerships with sustainability-focused local businesses such as eco-tourism can motivate fishing community towards CE adoption. Strengthening recycling infrastructure by establishing accessible collection centers, especially in these coastal areas, and fostering collaborations with recycling companies to create markets for waste materials are also essential steps. Efforts taken in modifying fishing equipment concerning environmental reasons are minimal within these communities, which is also largely due to lack of technical training and awareness. The main barriers to adopting circular economy practices include lack of awareness, limited financial resources, inadequate technical support, and the absence of accessible recycling facilities. Despite these challenges, there is a notable willingness among stakeholders to engage in more sustainable practices if supported through infrastructure development, capacity building, and localized, harbor-specific interventions. Overall, the study suggests that with coordinated policy support and targeted community engagement, the fisheries sector in Sri Lanka holds strong potential to transition toward a more circular and sustainable operational model.

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Environmental Engineering Innovations For Sustainable Resource Management

COMPARISON OF ANAEROBIC CO-DIGESTION OF CHEESE WHEY WITH GARDEN WASTE AND KITCHEN WASTE

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Abstract: Cheese whey is considered a major waste in the dairy industry, particularly during cheese manufacturing. Approximately 9 liters of cheese whey are generated when producing 1kg of cheese. It contains large amounts of organic matter, including lactose, proteins, and fats, making it a challenging waste stream to manage when sent to wastewater treatment plants. Due to its high organic content this waste can be valorised as a raw material for biogas generation. This study focuses on enhancing biogas production from cheese whey through anaerobic co-digestion with kitchen and garden waste. The objective is to compare the biogas yield from anaerobic digestion of cheese whey alone and co-digestion of cheese whey with kitchen and garden waste. Three sets of digesters were used: one with cheese whey alone and two with garden waste and kitchen waste. The highest biogas generation was observed with co-digestion system with garden waste and it was 9.88 L per kg of volatile solids. Second highest yield was from cheese whey alone, which was 2.29 L per kg of volatile solids. The combination of cheese whey with kitchen waste resulted in the lowest biogas yield of 0.57 L per kg of volatile solids. These finding highlights the potential of co-digestion of cheese whey with garden waste and confirm that cheese whey is a viable feedstock for biogas production.

Keywords: Anaerobic digestion; Co-digestion; Cheese whey; Garden waste; Biogas production.

1. Introduction

Anaerobic digestion (AD) is a biological process where a diverse group of microorganisms decomposes organic matter in the absence of oxygen, leading to the production of biogas, a mixture primarily composed of methane (CH_4) and carbon dioxide (CO_2). Initially the AD was conceded as two-step process but further studies have found that the process is a complex fermentation process which consists of four major steps. It consists of hydrolysis, acidogenesis, acetogenesis, and methanogenesis. Each step plays a critical role in the overall process of breaking down organic matter and generating biogas.

At the first stage which is known as hydrolysis, is the step where the large organic polymers break down or depolymerizes by acidogenic bacteria. Hydrolysis is a slow step, which can limit the rate of the overall anaerobic digestion process. Especially when using solid waste as the substrate the hydrolysis step is the rate-limiting stage that determines the rate of the overall process (Laiq Ur Rehman et al., 2019).

During acidogenesis, the monomers produced in hydrolysis are further broken down by acidogenic (fermentative) bacteria into volatile fatty acids (VFAs), alcohols, hydrogen, carbon dioxide, and other by-products. This stage generates intermediate compounds and leads to a decrease in pH, which must be controlled to avoid process inhibition.

In the acetogenesis step, the volatile fatty acids produced in acidogenesis are converted into acetic acid, hydrogen, and carbon dioxide by acetogenic bacteria. These simpler compounds are the direct precursors needed for the final step of methane production. The hydrogen produced during the acetogenesis is a waste since it inhibits the metabolism of the acetogenic bacteria. Still, hydrogen is consumed by methane-producing bacteria (Bajpai, 2017).

The final step which is methanogenesis is crucial to anaerobic digestion since the methanogenic bacteria are slow growing and extremely sensitive to the changes in the environment, and these bacteria will only absorb narrow array of simple substrates, such as formic acid, acetic acid, methanol, carbon monoxide, carbon dioxide and hydrogen to methane. Methane producing bacteria are strictly anaerobic and vulnerable for even small amounts of oxygen. The methane producing bacteria can be divided into acetophilic bacteria, hydrogenophilic bacteria, and methylophilic bacteria.

Anaerobic co-digestion is a process in which two or more different types of organic waste materials are digested together under anaerobic conditions. The combination of various waste streams can improve the efficiency and stability of the digestion process, enhancing biogas production. The goal of co-digestion is to improve nutrient balance, achieve higher methane yields, and optimize the overall performance of the anaerobic digestion system.

Anaerobic co-digestion of livestock effluents and agricultural residues is widely applied in Europe, and several studies found that the treatment of raw cheese whey was a concern due to the tendency for rapid acidification. The other challenges and inefficiencies associated with the direct anaerobic digestion of whey are reactor instability, difficulty in granulation, and Excessive Production of Viscous Exopolymer Materials (Comino, Riggio and Rosso, 2012). Therefore, most of the researchers have concluded that co-digestion with different manure will enhance the efficiency of the process.

While several studies have demonstrated the benefits of co-digestion, there remains a lack of comprehensive analysis regarding the optimal substrate ratios and the interplay between different waste components, particularly when combining cheese whey with garden and kitchen waste. This study aims to fill these gaps by systematically comparing biogas yields, analyzing key parameters such as VS, TS, and C/N ratios, and assessing the overall process stability. Furthermore, by incorporating recent findings on process inhibition and scalability (Ahmad et al., 2024), this work offers new insights into achieving efficient and robust anaerobic digestion suitable for industrial applications.

2. Materials & Method

2.1 Materials

Cheese whey, garden waste, and kitchen waste were used as the substrate for the process, and inoculum collected from an existing digester was used as the microbial source for the digestion process. Cheese whey was collected from a domestic-scale cheese production facility in Kurunegala. Garden waste was collected from the university farm as they collect grass from the whole university for feeding the cows in the farm, and it ensures the homogeneity in the materials used. Kitchen waste, which is typically characterized as having high levels of protein, carbohydrates, and fat was collected from the canteen at the Faculty of Engineering. The inoculum, which is necessary for providing the microbial activities, was collected from the anaerobic digester in the veterinary farm of University of Peradeniya.

2.2 Method

The experimental apparatus, comprising six identical digesters, was designed following the water displacement method for gas collection. The water displacement method was used as it is simple, accurate, and suitable for small-scale laboratory setups. Figure 1 shows a digester set up arranged with the locally available containers. The gas collection setup was arranged using a 250 ml beaker and a 100 ml measuring cylinder, and a wooden support was used to keep the setup vertically stable. Each digester was connected to a gas collection system, and the collected gas was measured by a calibrated scale on the measuring cylinder.



Figure 1: Experimental Digester setup

The experiment was designed to compare the biogas production of mono-digestion of cheese whey and of co-digestion with garden waste and kitchen waste. All the digesters were labeled from 1 to 6.

Digesters labeled as 1 and 2 were filled with 1200 g of cheese whey alone. According to the given quantities in Table 1, digesters labeled as 3 and 4 were filled with cheese whey mixed with kitchen waste, and digesters 5 and 6 were filled with a mixture of cheese whey and garden waste.

Due to the limited volume of the digesters, it was not feasible to add the full intended amount of garden waste. To accommodate this constraint, the garden waste mass was reduced in the co-digestion treatment. To overcome this inconsistency when comparing results across different treatments, all biogas production data were normalized and expressed as milliliters per 100 g of substrate. This normalization ensures that the gas yields from all digesters can be directly compared, despite the variations in the total substrate mass used in each treatment.

Table 1: Mass composition of digester feed

Components	Digester number		
	1 - 2	3 - 4	5 - 6
Cheese whey (g)	900	450	100
Garden Waste (g)	-	-	100
Kitchen Waste (g)	-	450	-
Inoculum (g)	300	300	66

All the digesters were replicated. Bio gas generation was observed for 20 days, and the data that was obtained was recorded as a cumulative gas volume, ml/100 g of substrate.

At the beginning of the experiment VS, TS values of the digesters were calculated since the analysis of VS and TS levels provides more insights of the substrate performance. The lower the TS value higher the initial rate of gas production can be observed (Liotta *et al.*, 2014). Table 2 shows the measured TS and VS content for the substrate used in the experiment.

The following procedures were used to calculate the TS and VS values of the samples. The total solids (TS) of the digester can be divided into the total volatile solids (VS) and the total fixed solids (FS) of the digester substrates.

$$TS = VS + FS \quad (1)$$

$$Total\ Solids\% = \frac{Weight\ of\ dry\ Sample}{Weight\ of\ wet\ Sample} \times 100 \quad (2)$$

$$Volatile\ Solids\% = \frac{Weight\ of\ dry\ Sample - Weight\ of\ Ash}{Weight\ of\ dry\ Sample} \times 100 \quad (3)$$

For determining the weight of the dry sample, the wet sample was dried using an oven at 105°C until a constant weight was achieved. The weight loss during drying is the water content, and the remaining weight is the TS. The dried sample was incinerated in a muffle furnace at 550°C for 1 hour to obtain the ash weight, which is equivalent to the fixed solids. The weight lost during the combustion process represents the VS, which indicates the amount of organic matter present (Mauer and Bradley, 2017).

After the above procedure using equations (1), (2), and (3) the VS and TS values of the digesters were found. Table 2 shows the VS and TS values of each digester.

Table 2: Calculated VS, TS and VS/TS of substrates

Digester	Volatile Solids (%)	Total Solids (%)	VS/TS
CW	34.43	84.13	0.41
CW with KW	49.59	68.38	0.72
CW with GW	26.43	43.04	0.61

Biogas production data were primarily analyzed through graphical representation. Daily and cumulative biogas yields (expressed in ml per 100 g of substrate) were plotted to compare the performance of each digester setup. Although no formal statistical tests were conducted, trends and differences between the feedstock treatments were visually assessed. In future studies, using statistical tests could further validate the observed differences.

3. Results and Discussion

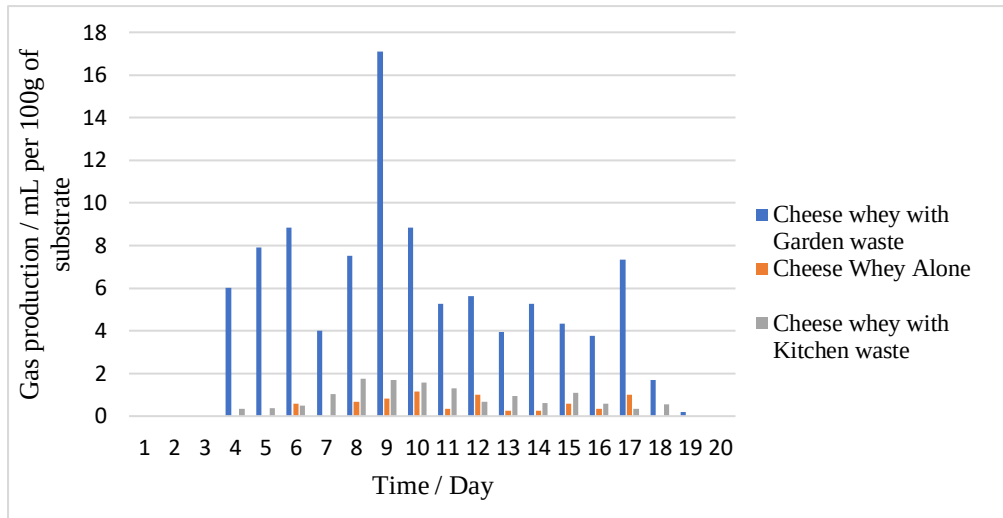


Figure 2: Daily Gas Collection of each Digester.

Figure 2 shows that the digesters with the cheese whey and garden waste mixture-initiated gas production on the 4th day of the experiment. Digesters containing the cheese whey and kitchen waste mixture began producing gas on the 5th day, while those with cheese whey alone exhibited a longer lag phase. The cheese whey and garden waste mixture produced gas continuously for 15 days.

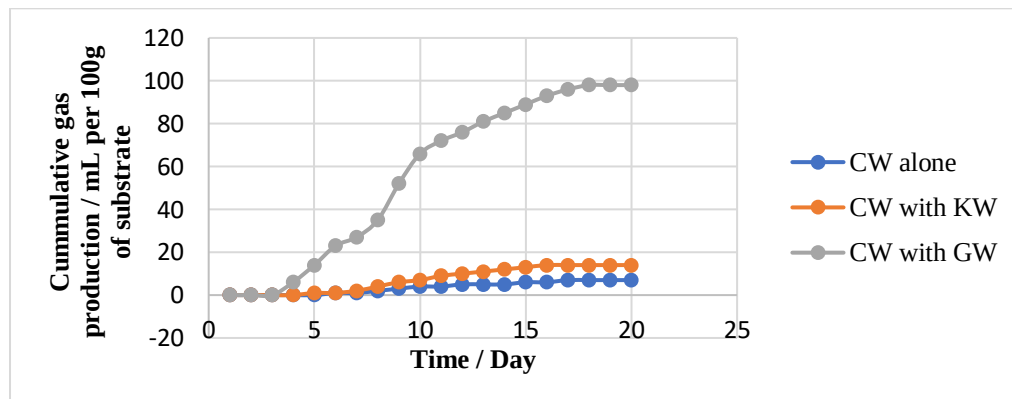


Figure 3: Cumulative Gas Production with three digester setups

Figure 3 represents the cumulative gas production of each digester throughout the 20 days that the experiment carried out.

Table 3: Yield of each Digester in ml per g of Volatile Solid

Digester	Gas Volume (ml)	Yield (ml/ g VS)
CW	79	2.29
(Kim and Kim, 2020) CW with KW	85.5	0.57
CW with GW	261	9.88

Figure 3 and Table 3 show the cumulative biogas production over 20 days for each digester setup. The highest gas production, 9.88 ml/g VS, was observed in the digester with cheese whey and garden waste. This was followed by 2.29 ml/g VS for cheese whey with kitchen waste and 0.57 ml/g VS for cheese

whey only. The garden waste mixture exhibited a shorter lag phase of only 4 days and produced gas for a period of 15 days, making it the most efficient mixture. The high performance of this combination can be due to the cellulose and fibrous components present in garden waste, which significantly improve the carbon-to-nitrogen (C/N) ratio. This balanced ratio provided favourable conditions for microbial activity, leading to improved biogas yield and process stability (Kim and Kim, 2020)(Laiq Ur Rehman *et al.*, 2019)

In contrast, the digesters with cheese whey alone and cheese whey with kitchen waste demonstrated longer lag phases and lower overall yields. The delayed microbial adaptation in these setups indicates that the substrates lacked the optimal conditions necessary for rapid and efficient microbial activity. Cheese whey alone suffered from a severely unbalanced C/N ratio due to its low carbon content, which limited microbial activity, reduced biodegradability, and ultimately resulted in minimal gas production (Zhang *et al.*, 2014)(Keating, 2014). The excessive nitrogen content in kitchen waste disturbs the C/N ratio in the cheese whey and kitchen waste mixture. This excess nitrogen will accumulate in the digester as ammonia and volatile fatty acids like lactic and acetic acids, which will lead to reduce microbial activity and low methane yield (Yen and Brune, 2007, Chen, Cheng and Creamer, 2008). The findings underscore the importance of maintaining an appropriate nutrient balance to achieve optimal biogas production.

The composition of the substrates played a critical role in the efficiency and performance of each digester. The VS and TS content of the substrates, as shown in Table 2, provide key insights into their impact on biogas yield. The mixture of cheese whey and garden waste exhibited the lowest TS value (43.04%) and a well-balanced VS/TS ratio, which helped the hydrolysis and sustained microbial activity throughout the digestion process. Lower TS levels are particularly beneficial as they improve substrate accessibility and promote interaction between microorganisms and organic matter. This ultimately leads to higher gas production rates and process stability (Liotta *et al.*, 2014, Ahmad *et al.*, 2024).

While an appropriate level of ammonia provides a buffering effect, excess ammonia inhibits methanogenic activity (Shahbaz *et al.*, 2020). This excess ammonia will also inhibit the acetic acid metabolism in an anaerobic digestion system, the accumulation of acetic acid will inhibit the degradation of other VFAs (Yang *et al.*, 2024), creating an unfavourable environment for methanogenesis (Helena Perin *et al.*, 2020). This inhibition of microbial activity significantly reduced biogas production and highlights the need for effective mitigation strategies. Such strategies could include the use of buffering agents or adjustments in feedstock ratios to optimize the digestion process and address the challenges posed by acidification (Chen, Cheng and Creamer, 2008, Wang *et al.*, 2016).

Although cheese whey has a relatively high VS content, it yielded the lowest biogas production due to its unbalanced C/N ratio and limited nutrient diversity. This was primarily due to its low C/N ratio, leads to ammonia accumulation, which inhibits methanogenic activity and reduces biogas yield. Addition of a carbon-rich co-digestive material, such as garden waste effectively addressed these issues by balancing the C/N ratio (Shi *et al.*, 2013). This adjustment enhances process stability, microbial activity, and methane yield (Yadvika *et al.*, 2004, Ward *et al.*, 2008).

The lag phase observed in each digester setup provides valuable insights into the microbial adaptation process. The shortest lag phase (4 days) was observed in the cheese whey and garden waste mixture, indicating rapid microbial adaptation and an optimally balanced nutrient profile. The high cellulose and fibrous content of garden waste contributed to a favourable environment for microbial growth and activity, enabling faster hydrolysis and sustained gas production over an extended period of 15 days (Kim and Kim, 2017).

In contrast, cheese whey and kitchen waste mixture exhibited a significantly prolonged lag phase. This delay in microbial adaptation was primarily due to the inhibitory effects of ammonia, due to nitrogen

content in the substrate. Kitchen waste is highly soluble which resulting in fast degradation, which will lead to the accumulation of VFAs (Magdalena, Greses and González-Fernández, 2019). This VFAs and ammonia will create unfavourable environmental conditions for methanogenic bacteria, resulting in a slower and less efficient digestion process. To address these challenges, future research should explore pre-treatment methods, adjusting the feedstock composition or incorporating buffering agents, to improve microbial adaptation and overall process efficiency (Keating, 2014, Khalid *et al.*, 2011).

These results highlight the importance of selecting the right co-digestive materials to achieve higher biogas yields.

The results of this study highlight the effectiveness of co-digestion as a strategy to enhance biogas production. Among the tested setups, the addition of garden waste emerged as the most effective approach, yielding the highest biogas production and demonstrating superior process stability. The garden waste mixture successfully balanced the C/N ratio, improved substrate biodegradability, and supported sustained microbial activity.

Future studies should focus on optimizing co-digestion ratios, implementing advanced pre-treatment methods, and exploring the use of buffering agents to mitigate acidification and improve overall process performance. Additionally, further research is suggested to investigate the long-term stability and scalability of these co-digestion strategies for industrial applications.

4. Conclusion

Mainly in this study, the C/N ratio was adjusted by adding a carbon and nitrogen rich co components. The digesters that used co-digestion produce more gas comparing to digesting the cheese whey alone. Summary of Key Findings

- Cheese Whey and Garden Waste: This combination produced the highest biogas yield (9.88 ml/g VS), exhibited the shortest lag phase (4 days), and maintained sustained gas production for 15 days. The balanced C/N ratio and efficient hydrolysis contributed to its superior performance.
- Cheese Whey alone: The lowest biogas yield (0.57 ml/g VS) was observed in this setup due to the unbalanced C/N ratio, which limited microbial activity and methane production.
- Cheese Whey and Kitchen Waste: Despite its potential, this setup demonstrated poor performance (2.29 ml/g VS) due to excessive nitrogen content, which lead to ammonia accumulation and inhibited microbial activity.

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MULTI-CRITERIA DECISION MAKING APPROACH FOR SELECTING THE OPTIMAL METHOD FOR ANTIBIOTIC REMOVAL FROM WASTEWATER**E. S. K. Zoysa*, S. Indika***Department of Chemical and Process Engineering, Faculty of Engineering, University of Peradeniya, Sri Lanka.*** Correspondence E-mail: e18407@eng.pdn.ac.lk, TP: +94721586620*

Abstract: The increasing presence of antibiotics in wastewater from hospitals, pharmaceutical industries, and agriculture has been identified as a significant environmental and public health risk due to the persistence of antibiotics and the proliferation of antibiotic-resistant bacteria (ARB) and resistance genes (ARGs). Traditional wastewater treatment plants have often been found to be ineffective in completely removing these contaminants. In this study, a Multi-Criteria Decision Making (MCDM) approach was applied to select the optimal antibiotic removal method, with both biological and non-biological treatment technologies evaluated based on amoxicillin removal efficiency, processing time, and Chemical Oxygen Demand (COD) removal efficiency. The PROMETHEE (Preference Ranking Organization Method for Enrichment of Evaluations) technique was utilized to rank various treatment methods. The final results indicated that membrane filtration was the most effective method, achieving a high amoxicillin removal efficiency of 94.5%, a short processing time of 19 minutes, and an impressive COD removal efficiency of 97%. These findings demonstrate that membrane filtration provides a balanced approach to efficiency, speed, and water quality improvement. The study emphasizes the value of MCDM in optimizing antibiotic removal strategies, contributing to sustainable wastewater management, and reducing the environmental impact of antibiotic pollution.

Keywords: Antibiotic pollution; Wastewater treatment; Antibiotic removal; Amoxicillin; Biological degradation

1. Introduction

The presence of antibiotic residues in medical wastewater has become a significant environmental concern due to their persistence and potential to induce antimicrobial resistance (AMR). Hospitals, pharmaceutical industries, and healthcare facilities discharge wastewater containing a variety of antibiotics, including β -lactams, fluoroquinolones, sulfonamides, and tetracyclines, which conventional wastewater treatment plants (WWTPs) often fail to remove efficiently (Kümmerer, 2009). These residues not only contaminate natural water bodies but also disrupt aquatic ecosystems, altering microbial community structures and promoting the spread of ARB and ARGs (Rizzo et al., 2013).

Antibiotic residues pose serious risks to the environment and human health. Persistent antibiotics in water can bioaccumulate in aquatic organisms, causing toxic effects at all trophic levels (Grenni, Ancona, & Caracciolo, 2018). Furthermore, the increasing amount of ARGs in wastewater effluents contributes to the global challenge of antibiotic resistance, reducing antibiotic efficacy in human and veterinary medicine (Berendonk et al., 2015). Long-term exposure to low levels of antibiotics in drinking water may also lead to adverse health effects in humans, such as allergic reactions and disruption of gut microbiota (Kraemer, Ramachandran, & Perron, 2019).

To mitigate these risks, a variety of treatment methods have been explored, broadly categorized into biological and non-biological approaches. Biological methods, including bacterial, fungal, and microalgal biodegradation, offer eco-friendly and cost-effective solutions by leveraging microbial metabolism and enzymatic activity to break down antibiotics into non-toxic byproducts (Ahmed et al., 2017). Microalgal treatment has gained attention for its dual capability of antibiotic removal and biomass production, while bacterial and fungal degradation pathways also demonstrate high efficiency (Matamoros et al., 2016).

In addition to biological methods, non-biological approaches such as adsorption, membrane filtration, and advanced oxidation processes (AOPs) have shown promise in antibiotic removal from wastewater. Adsorption using materials like activated carbon offers high removal efficiency but may lead to secondary pollution through spent adsorbent disposal (Nugraha et al., 2025). Membrane filtration techniques, including nanofiltration and reverse osmosis, provide effective separation of antibiotics but are often associated with high operational costs and membrane fouling (Zhang et al., 2021). AOPs, involving ozonation, photocatalysis, and Fenton's reagent, generate reactive species capable of degrading antibiotic molecules; however, they may require substantial energy inputs and pose a risk of forming harmful by-products (Merchant et al., 2024). This review aims to critically evaluate both biological and non-biological treatment methods for antibiotic removal from medical wastewater.

2. Antibiotic Pollution in Wastewater: Focus on Amoxicillin

The extensive use of antibiotics across healthcare, veterinary, and agricultural sectors has led to their persistent release into wastewater systems, posing significant environmental and public health risks (Kümmerer, 2009). Hospitals, pharmaceutical industries, and domestic wastewater are major contributors to antibiotic pollution, as a considerable proportion of antibiotics are excreted in unmetabolized or active forms (Rizzo et al., 2013). In agriculture, antibiotics used for disease control and growth promotion in livestock and aquaculture enter water bodies through manure runoff, slurry, and direct discharge, contributing to the contamination of surface waters, sediments, and groundwater (Zhang et al., 2022).

Conventional WWTPs are generally ineffective at removing antibiotics, allowing these contaminants to persist in effluents and accumulate in natural water systems (Matesun et al., 2024). In the environment, antibiotics undergo biodegradation, photodegradation, hydrolysis, and adsorption to sediments, with removal efficiency influenced by pH, temperature, and microbial activity (Liu et al., 2019). However, partial degradation can lead to the formation of toxic metabolites, extending the ecological impact of antibiotic residues (Kumar, et al., 2019). These persistent contaminants exert selective pressure on

microbial communities, promoting the spread of ARB and ARGs, which pose serious threats to human and animal health (Berendonk et al., 2015).

The ecological consequences of antibiotic pollution include disruptions in microbial diversity, nutrient cycling, and adverse effects on non-target species, such as algae, invertebrates, and fish (Grenni, Ancona, & Caracciolo, 2018; Wang et al., 2021). Groundwater contamination exacerbates concerns regarding drinking water safety and the spread of antimicrobial resistance, highlighting the need for advanced wastewater treatment technologies, stricter regulations, and responsible antibiotic use to mitigate environmental and health risks (Kraemer, Ramachandran, & Perron, 2019).

Among the numerous antibiotics present in wastewater, amoxicillin, a β -lactam antibiotic, stands out due to its widespread use in both human healthcare and veterinary medicine (Kümmerer, 2009). Its high solubility, stability, and broad-spectrum application contribute to its frequent detection in wastewater, often persisting through conventional treatment processes (Al-Tohamy et al., 2022). The chemical structure of amoxicillin, particularly its β -lactam ring, is resistant to hydrolysis and many biodegradation pathways, presenting significant challenges for wastewater treatment (Rizzo et al., 2013).

Given its prevalence and persistence, amoxicillin serves as an ideal model antibiotic for studying antibiotic contamination and developing effective removal strategies. Insights gained from amoxicillin's degradation mechanisms can contribute to broader efforts to combat antibiotic pollution and antimicrobial resistance, offering valuable guidance for selecting optimal wastewater treatment methods (Zhang et al., 2022).

3. Chemical and Physical Techniques for Antibiotic Removal

Chemical and physical methods for antibiotic removal from wastewater are gaining significant attention due to their high efficiency, fast action, and versatility across various types of wastewater. These approaches use a range of physical, chemical, and physicochemical processes to either degrade, transform, or separate antibiotics, presenting a robust alternative to biological treatments (Kümmerer, 2009). Techniques such as AOPs, membrane filtration, adsorption, electrochemical methods, and chemical precipitation have shown considerable promise in removing a wide spectrum of antibiotics, including β -lactams, fluoroquinolones, sulfonamides, and tetracyclines (Rizzo et al., 2013).

Unlike biological methods, which depend on microbial activity, chemical and physical treatments can often achieve quicker removal rates and target non-biodegradable compounds (Wu et al., 2012). For example, AOPs generate highly reactive radicals that can break down antibiotics into non-toxic byproducts, while membrane filtration physically removes antibiotics from wastewater (Zhang et al., 2022). However, many non-biological methods come with high operational costs, greater energy consumption, and the possibility of creating toxic byproducts, necessitating careful optimization of the treatment conditions (Abdelfattah et al., 2023). As concerns over antibiotic pollution and the growing issue of AMR continue to rise, integrating chemical and physical methods with biological treatments or developing hybrid systems offers promise for improving overall wastewater treatment efficiency (Pham et al., 2024).

3.1 Advanced Oxidation Processes

AOPs are highly effective chemical treatment methods for removing antibiotics from wastewater through the generation of highly reactive radicals, primarily hydroxyl radicals ($\bullet\text{OH}$). These radicals have a strong oxidation potential, enabling the degradation of a wide range of antibiotics, including β -lactams, fluoroquinolones, sulfonamides, and tetracyclines, into non-toxic byproducts (Rizzo et al., 2013). Common AOPs include ozonation, photocatalysis, Fenton and photo-Fenton reactions, and ultraviolet (UV) irradiation, often used alone or in combination to enhance treatment efficiency (Rekhate et al., 2020).

One of the key advantages of AOPs is their ability to mineralize organic pollutants, effectively reducing antibiotic residues and AMR risks in treated wastewater (Akbari, et al., 2021). However, the efficiency of these processes depends on factors such as pH, temperature, antibiotic concentration, and the presence of inorganic and organic matter in the wastewater (Zhang et al., 2022). Despite their high efficiency, AOPs can have drawbacks, including high operational costs, energy consumption, and the potential formation of toxic byproducts, such as bromate in ozonation (Maniakova et al., 2023). Therefore, AOPs are often integrated with biological treatments or used as pre-treatment steps to enhance the overall wastewater treatment process (Kümmerer, 2009).

3.2 Membrane Filtration Technologies

Membrane Filtration Technologies are widely used in wastewater treatment for the removal of antibiotics and other micropollutants through physical separation mechanisms. These technologies employ semi-permeable membranes that act as a barrier, allowing water to pass through while retaining antibiotic molecules, microorganisms, and suspended solids (Xue et al., 2025). The most commonly used membrane filtration techniques include microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), and reverse osmosis (RO), each offering varying degrees of pore size and selectivity (Zhang et al., 2022).

RO and NF are particularly effective in antibiotic removal, as they can block small molecules and even ions, achieving high rejection rates for a wide range of antibiotics, including β -lactams, tetracyclines, and fluoroquinolones (de Ilurdoz et al., 2022). However, the performance of membrane technologies is influenced by fouling, which reduces permeability and efficiency over time. Membrane fouling is often caused by organic matter, biofilms, and inorganic deposits, necessitating frequent cleaning and membrane replacement, which can increase operational costs (Akbari, et al., 2021).

Despite these challenges, membrane filtration technologies offer several advantages, including low chemical usage, modular design, and consistent water quality (Rizzo et al., 2013). In recent years, the integration of membrane processes with biological treatments or AOPs has shown promise in enhancing antibiotic removal efficiency and mitigating membrane fouling (Kümmerer, 2009). These hybrid approaches hold potential for improving antibiotic removal from wastewater and reducing the environmental impact of antibiotic pollution.

3.3 Adsorption Techniques

Adsorption techniques are widely employed in the removal of antibiotics from wastewater due to their simplicity, cost-effectiveness, and high efficiency. This technique involves the adhesion of antibiotic molecules to the surface of a solid material, known as the adsorbent, through physical or chemical interactions (Mangla et al., 2022). Common adsorbents used for antibiotic removal include activated carbon, clay minerals, biochar, mesoporous materials, and carbon nanotubes. These materials have large surface areas, porosity, and functional groups that enhance their adsorption capacity for various contaminants, including β -lactams, fluoroquinolones, tetracyclines, and sulfonamides (Rizzo et al., 2013).

The adsorption process is influenced by factors such as pH, temperature, antibiotic concentration, and the surface properties of the adsorbent. For instance, activated carbon is known for its high surface area and high adsorption capacity, making it effective for a wide range of antibiotics (Akbari et al., 2021). However, adsorption can be either reversible or irreversible, depending on the type of interactions involved. Physisorption, which relies on weak forces such as van der Waals interactions, is generally reversible, allowing adsorbed antibiotics to be released back into the water if conditions change or the adsorbent reaches saturation (Zhang et al., 2022). To improve the efficiency of adsorption techniques, researchers are actively exploring the development of composite adsorbents and methods for the regeneration of adsorbents.

One of the primary advantages of adsorption is its ability to target non-biodegradable and non-oxidizable antibiotics, which may not be effectively removed by conventional techniques (Guillosou et al., 2020). However, the main limitations of adsorption techniques are the high operational costs related to the purchase and regeneration of adsorbents and the potential for adsorbent fouling (Kümmerer, 2009). Despite these challenges, adsorption remains a promising method for antibiotic removal from wastewater, especially when integrated with other treatment technologies, such as membrane filtration or AOPs.

3.4 Electrochemical Methods

Electrochemical Methods are emerging as a promising approach for the removal of antibiotics from wastewater due to their high efficiency, selectivity, and ability to degrade a wide range of contaminants. These methods utilize electrochemical reactions at the surface of electrodes to degrade or transform antibiotics into non-toxic byproducts (Rizzo et al., 2013). The process typically involves applying a current to electrodes submerged in wastewater, which generates reactive oxygen species (ROS), such as hydroxyl radicals ($\bullet\text{OH}$), peroxide ions ($\text{O}_2\bullet^-$), and superoxide anions (O_2^-), that can oxidize and decompose antibiotics (Zhang et al., 2022).

Electrochemical oxidation and electro-Fenton processes are the most commonly used electrochemical methods for antibiotic removal. In these processes, Fenton reagents (e.g., iron ions and hydrogen peroxide) are used in combination with electrodes to generate hydroxyl radicals capable of mineralizing antibiotics, such as fluoroquinolones, β -lactams, and tetracyclines (Razzaq et al., 2024). These methods are advantageous because they can achieve high degradation efficiencies without the need for external chemical reagents and can target a broad spectrum of pollutants, including those that are non-biodegradable (Akbari et al., 2021).

However, the application of electrochemical methods also presents several challenges. The energy consumption required to sustain the electrochemical reactions can be high, particularly in large-scale operations, making these methods cost-prohibitive in some cases (Gurkan et al., 2021). Furthermore, the selectivity of the process can be influenced by factors such as electrode material, current density, pH, and the concentration of antibiotics, which may require careful optimization (Kümmerer, 2009). Despite these challenges, electrochemical methods are gaining attention for antibiotic removal because they offer advantages over traditional methods, including the ability to mineralize antibiotics into harmless byproducts, the minimal need for chemicals, and the potential for on-site treatment (Rizzo et al., 2013). Future developments in electrode materials, process optimization, and integration with other treatment technologies could further enhance the economic viability and effectiveness of electrochemical methods in addressing antibiotic pollution in wastewater.

4. Biological Methods for Antibiotic Removal

Biological methods for the removal of antibiotics from wastewater are gaining widespread attention due to their cost-effectiveness, sustainability, and ability to completely mineralize contaminants. These methods employ microorganisms to biodegrade or transform antibiotics into less toxic or inert compounds, which provides a distinct advantage over chemical and physical treatments by minimizing the production of secondary pollutants. While chemical methods such as AOPs and chlorination are effective in breaking down antibiotics, they may produce harmful byproducts and incur high operational costs (Rizzo et al., 2013). Similarly, physical methods like adsorption and membrane filtration generally transfer contaminants to another phase, necessitating additional treatment steps to achieve complete removal (Kamalesh et al., 2024).

Several biological approaches, including microalgal, bacterial, and fungal biodegradation, enzyme-based degradation, microbial consortia, and anaerobic digestion, have demonstrated considerable potential in degrading a wide range of antibiotics such as sulfonamides, tetracyclines, fluoroquinolones, and β -lactams (Akbari et al., 2021). The efficiency of these methods is influenced by factors such as

antibiotic concentration, wastewater characteristics, and environmental conditions. As antibiotic pollution becomes an increasing concern for both the environment and public health, the optimization and enhancement of biological treatment technologies are essential for improving the effectiveness and sustainability of wastewater treatment systems (Kümmerer, 2009).

4.1 Microalgal biodegradation

Microalgal biodegradation has emerged as a promising, environmentally friendly method for removing antibiotics from wastewater. This approach leverages the metabolic capabilities of microalgae to absorb, transform, and degrade pharmaceutical contaminants. Various antibiotics, including sulfonamides, fluoroquinolones, and tetracyclines, have been successfully degraded by microalgae species such as *Chlorella*, *Scenedesmus*, and *Chlamydomonas* (Li et al., 2024). The primary mechanisms involved in this process include bioaccumulation, biotransformation, and photodegradation. Bioaccumulation occurs when microalgae absorb antibiotics through passive diffusion or active transport across the cell membrane. Once inside the cells, biotransformation is facilitated by intracellular enzymes such as cytochrome P450 monooxygenases and laccase-like enzymes, which degrade the complex antibiotic molecules into simpler, less toxic metabolites (Moo-Young, 2019). Additionally, microalgae can enhance antibiotic removal through photodegradation. Under light exposure, they produce ROS like hydroxyl radicals and singlet oxygen, which help to oxidize and break down antibiotics in the surrounding water (Xiong et al., 2021). This combined effect of biodegradation and photodegradation significantly improves the degradation of persistent antibiotics.

Microalgae also remove nutrients, such as nitrogen and phosphorus, from wastewater, promoting their growth and enhancing biodegradation efficiency (Abdel-Raouf et al., 2012). This dual function not only prevents eutrophication but also contributes to the sustainability of microalgal systems. Another advantage is the potential for resource recovery, as the biomass generated during the treatment process can be harvested for bioenergy production, animal feed, or biofertilizers (Mu et al., 2021). Compared to traditional chemical and physical methods, microalgal biodegradation is cost-effective, environmentally friendly, and energy-efficient. However, challenges remain in optimizing this technology, such as selecting high-performance strains, fine-tuning operational parameters (e.g., light intensity, pH, and nutrient availability), and scaling up for industrial applications (Kuppan et al., 2024).

4.2 Bacterial biodegradation

Bacterial biodegradation is an effective biological method for removing antibiotics from wastewater. Certain bacterial species can break down a variety of antibiotics, including tetracyclines, fluoroquinolones, sulfonamides, and β -lactams, thanks to their specialized enzymatic systems (Abdelfattah et al., 2023). These bacteria mineralize antibiotics into harmless byproducts such as carbon dioxide, water, and inorganic salts by utilizing the antibiotics as carbon, nitrogen, or energy sources. Enzymes like laccases, peroxidases, monooxygenases, and β -lactamases play a crucial role in breaking down complex antibiotic molecules into simpler, less toxic metabolites (Mora-Gamboa et al., 2022).

Bacterial biodegradation can occur under both aerobic and anaerobic conditions, depending on the bacterial species and environmental factors such as temperature, pH, and oxygen availability. Aerobic bacteria, including *Pseudomonas*, *Bacillus*, and *Acinetobacter*, are highly efficient in antibiotic degradation due to their diverse metabolic pathways and rapid growth rates (Xiong et al., 2021). On the other hand, anaerobic bacteria, such as *Clostridium* and *Methanosaeta*, play a crucial role in the reductive dechlorination of antibiotics, particularly chlorinated compounds (Bunge et al., 2003). Co-metabolism, where bacteria degrade antibiotics in the presence of other substrates, further enhances biodegradation efficiency and helps reduce the development of antibiotic resistance. Despite its effectiveness, bacterial biodegradation faces challenges such as the emergence of antibiotic-resistant bacteria and the accumulation of toxic byproducts. Additionally, environmental fluctuations, including changes in pH and temperature, can impact bacterial activity and degrade efficiency (Perez-Bou et al., 2024).

4.3 Fungal biodegradation

Fungal biodegradation presents a promising method for the removal of antibiotics from wastewater, harnessing the remarkable degradative abilities of fungi, particularly white-rot fungi. Species like *Phanerochaete chrysosporium*, *Trametes versicolor*, and *Ganoderma lucidum* produce potent extracellular enzymes such as lignin peroxidases, manganese peroxidases, and laccases (Grelska et al., 2020). These enzymes enable the oxidative cleavage of aromatic rings in complex antibiotic molecules, transforming them into simpler, less toxic compounds, which can then be further mineralized into harmless end products like carbon dioxide and water (Alaidaroos & B.A., 2023).

Fungal biodegradation can occur under both aerobic and anaerobic conditions, with aerobic processes typically offering higher efficiency due to the enhanced activity of fungal enzymes in oxygen-rich environments. Fungi have demonstrated the ability to degrade a wide range of antibiotics, including challenging compounds like β -lactams, tetracyclines, and fluoroquinolones, which are often resistant to conventional treatment methods (Mastropetros et al., 2022). The high tolerance of fungi to antibiotic toxicity allows them to thrive in wastewater systems with elevated contaminant concentrations. By incorporating fungal cultures for antibiotic degradation, the environmental impact of pharmaceutical pollutants can be reduced, and the potential for integrating fungal systems with other biological treatments, such as bacterial or microalgal systems, could further enhance removal efficiency (Akerman-Sanchez & Rojas-Jimenez., 2021). Despite the promising capabilities, fungal biodegradation requires optimized conditions such as appropriate pH, temperature, and nutrient levels to maximize effectiveness. Additionally, scaling up this process for large-scale applications poses challenges, and careful monitoring is necessary to avoid the accumulation of toxic byproducts.

4.4 Enzyme-based biodegradation

Enzyme-based degradation is an effective and environmentally friendly biological method for removing antibiotics from wastewater. This technique involves utilizing specific enzymes—either naturally occurring or genetically engineered—to catalyze the breakdown of antibiotic molecules into less harmful products. Enzymes such as laccases, peroxidases, oxidoreductases, and hydrolases are essential in biodegrading a wide range of antibiotics, including β -lactams, sulfonamides, tetracyclines, and fluoroquinolones (Xu et al., 2024). For instance, laccases can oxidize the aromatic structures of antibiotics, leading to bond cleavage and subsequent breakdown of the compound (Huong et al., 2020). Peroxidases, on the other hand, aid in the oxidation of antibiotics by generating reactive oxygen species (ROS), which enhances the degradation process (He et al., 2017).

One of the primary advantages of enzyme-based degradation is its specificity, as certain enzymes target particular antibiotic classes, thus minimizing the formation of toxic byproducts (Bittencourt et al., 2023). Compared to conventional treatment methods, enzyme-based degradation is more cost-effective and energy-efficient, as it operates under favorable conditions such as neutral pH and moderate temperatures (Aragaw et al., 2024). The efficiency of antibiotic removal can be further enhanced by combining enzymes with other biological treatments, such as bacterial or fungal systems (Imwene et al., 2022). However, challenges remain, including the high production costs of enzymes, the need to maintain enzyme stability, and the optimization of operating parameters such as pH, temperature, and enzyme concentration (Mao et al., 2024). Additionally, attention must be paid to the potential formation of intermediate compounds or hazardous byproducts. Despite these challenges, enzyme-based degradation remains a practical and eco-friendly approach to treating antibiotic-contaminated wastewater.

5. Multi criteria decision making

Multi criteria decision making (MCDM) offers a robust approach for selecting the most effective antibiotic removal method by balancing removal efficiency, processing time, and Chemical Oxygen Demand (COD) removal efficiency in wastewater treatment. By comparing biological methods and

non-biological methods, MCDM enables stakeholders to prioritize criteria based on specific treatment contexts, providing a systematic approach to decision-making (Triantaphyllou, 2000).

a. Comparative analysis

Table 1 summarizes chemical and physical methods for amoxicillin removal, along with key selection criteria. Removal efficiency denotes the percentage reduction in amoxicillin concentration achieved by the treatment process. Processing time refers to the duration required for the treatment to reach effective removal levels. COD removal efficiency represents the percentage decrease in chemical oxygen demand, indicating the method's effectiveness in eliminating organic pollutants from water. The table also highlights the specific limitations associated with each method.

Table 1: Chemical and Physical Methods for Amoxicillin Removal and Selection Criteria

Biological Methods	Amoxicillin Removal Efficiency (Representative Value, %)	Processing Time (Average, min)	COD removal efficiency (%)	Limitations	References
AOPs (Photo-Fenton)	100	30	66	- Requires acidic conditions (pH ~2.8–3), making pH adjustment necessary before and after treatment. - Iron salts produce sludge that requires additional treatment and disposal - Difficulties in scaling up from lab to industrial applications due to mass transfer limitations and maintaining optimal conditions.	Souza et al., 2018 Deng et al., 2015 Zhang et al., 2020 Chen et al., 2022
Membrane Filtration	94.5	19	97	- Organic matter, suspended solids, and amoxicillin residues can lead to fouling, reducing membrane efficiency and increasing maintenance needs. - Frequent membrane cleaning or replacement is required, contributing to high operational and maintenance costs	Liu et al., 2017 Wen et al., 1999 Peng et al., 2022
Adsorption (Activated Carbon)	95	360	39.4	- Adsorbents have a finite adsorption capacity, which may require frequent regeneration or replacement. - Adsorption efficiency can vary significantly with pH changes, as the ionization state of amoxicillin and surface charge of adsorbents are pH-dependent.	Liu et al., 2017 Ikhlaq et al., 2019 Tang et al., 2021 Peng et al., 2022
Electrochemical degradation	95	75	73.1	- The electrochemical process often requires significant electrical energy, particularly for high-strength wastewater, leading to increased operational costs. - High-performance electrode materials (e.g., boron-doped diamond, platinum) can be expensive and may not be cost-effective for large-scale applications.	Padilla-Robles et al., 2015 Rajkumar et al., 2004 Imarhiagbe et al., 2024 Jiang et al., 2023

In particular, adsorption efficiencies can vary widely depending on the type of adsorbent used. Different materials, including activated carbon, graphene-based composites, clays, and various modified materials, exhibit distinct adsorption capacities and removal efficiencies for amoxicillin.

The biological methods for amoxicillin removal are shown in Table 2, along with selection criteria including limitations, processing time, removal efficiency, and COD removal efficiency.

Table 2: Biological Methods for Amoxicillin Removal and Selection Criteria

Biological Methods	Amoxicillin Removal Efficiency (Representative Value, %)	Processing Time (Average, days)	COD removal efficiency (%)	Limitations	References
Microalgal biodegradation	31	7	67.5	- Factors such as light intensity, temperature, pH, and nutrient availability significantly affect microalgal growth and biodegradation efficiency. - While promising at the lab scale, scaling up microalgal systems for large-scale wastewater treatment involves challenges in maintaining culture stability and light distribution. - In natural or open systems, native microorganisms may outcompete microalgae, affecting the overall degradation efficiency.	Leng et al., 2020 Xiong et al., 2021 Shitu et al., 2024 Borowitzka et al., 2017
Bacterial biodegradation (aerobic conditions)	41.6	8	76	- Aerobic bacteria may not fully mineralize amoxicillin, leading to the formation of potentially toxic or persistent intermediates. - Aerobic processes require continuous aeration to maintain oxygen levels, leading to increased energy consumption and operational costs.	Yang et al., 2020 Busto et al., 2020 Zou et al., 2024
Bacterial biodegradation (anaerobic conditions)	33.5	15	70	- Anaerobic processes generally have slower microbial activity and degradation rates compared to aerobic conditions, leading to longer treatment times. - Anaerobic systems are highly sensitive to pH, temperature, and volatile fatty acid (VFA) accumulation, which can affect microbial community stability.	Yang et al., 2020 Kapdan et al., 2006 Chen et al., 2008
Fungal biodegradation	49	4	85.58	- Fungi are highly sensitive to pH, temperature, and nutrient availability, affecting biodegradation efficiency. - Certain fungi may not adapt well to wastewater conditions, particularly in the presence of complex or mixed pollutants. - Often requires pre-treatment of wastewater to adjust conditions suitable for fungal growth, increasing process complexity and cost.	Al-Shammari et al., 2024 Noorjahan et al., 2024 Maheshwari et al., 2000
Enzyme-based biodegradation	99.6	25	79.6	- Production, purification, and stabilization of enzymes (e.g., laccases, peroxidases) can be expensive, limiting large-scale applications. - Enzymes may lose activity under harsh environmental conditions, such as extreme pH, temperature, or the presence of inhibitory substances in wastewater. - High concentrations of amoxicillin or its intermediates may inhibit enzyme activity, reducing biodegradation efficiency.	Ahmed et al., 2017 Sutaoney et al., 2022 Mayer et al., 2002

It is important to note that the values presented for amoxicillin removal efficiency and processing time in Table 1 & 2 represent average or typical values reported across various studies.

4.2 PROMETHEE

PROMETHEE is an MCDM technique that evaluates and ranks alternatives based on various criteria through pairwise comparisons (Kalbar et al., 2012). In antibiotic removal from wastewater, PROMETHEE can assess methods by considering key criteria such as removal efficiency, processing time, and COD removal efficiency. The method uses preference functions to rank alternatives, helping decision-makers identify the best treatment method. PROMETHEE software streamlines this process and offers sensitivity analysis, effectively handling both quantitative and qualitative data (Pohl et al., 2024).

4.3 Critical analysis of different treatment techniques for antibiotics in wastewater

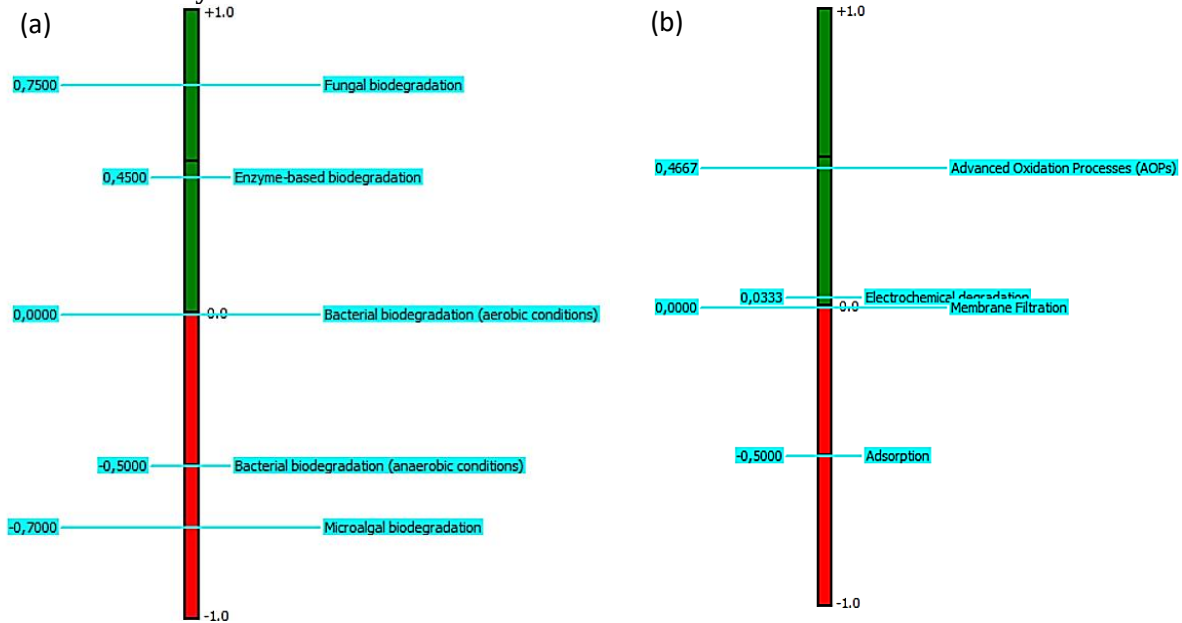


Figure 1: PROMETHEE complete ranking for (a) Chemical and Physical Methods, (b) Biological Methods

Figure 1 illustrates the PROMETHEE complete ranking, revealing that membrane filtration is the optimal method for amoxicillin removal. The ranking considered three critical criteria: amoxicillin removal efficiency, processing time, and COD removal efficiency, with weightages of 0.5, 0.2, and 0.3, respectively. Amoxicillin removal efficiency was given the highest weight (0.5) because achieving maximum pollutant elimination is the primary goal of wastewater treatment. High removal efficiency ensures effective treatment and compliance with environmental standards. Processing time was assigned a lower weight (0.2) to balance swift treatment processes with practical operational demands. While shorter processing times enhance efficiency, they should not compromise overall performance. COD removal efficiency was moderately weighted at 0.3, as reducing chemical oxygen demand is essential for improving water quality and minimizing ecological impacts.

In part (a), Advanced Oxidation Processes (AOPs), specifically the Photo-Fenton process, emerged as the top-performing chemical and physical method. Photo-Fenton demonstrated exceptional performance across all evaluated criteria, achieving a 100% removal efficiency of amoxicillin, which underscores its strong capability to eliminate the target antibiotic. Additionally, it offered a remarkably short processing time of just 30 minutes, aligning well with operational requirements for rapid treatment. Its chemical oxygen demand (COD) removal efficiency was also significant at 66%, indicating effective reduction of the overall organic load in treated water. This combination of complete pollutant removal, fast processing, and substantial COD reduction highlights AOPs (Photo-Fenton) as a well-rounded and practical solution for amoxicillin remediation.

In part (b), fungal biodegradation ranked highest among biological methods, reflecting its superior overall performance. Although the amoxicillin removal efficiency achieved was lower than that of chemical methods, at 49%, it still indicates notable potential for pollutant degradation through biological pathways. The process required a treatment duration of approximately four days, which, while longer than physical or chemical alternatives, remains reasonable within the context of biological systems. Notably, fungal biodegradation exhibited a high COD removal efficiency of 85.58%, signifying strong capability in reducing the organic load and improving water quality. This combination of effective pollutant removal, moderate processing time, and excellent COD reduction demonstrates the promise of fungal biodegradation as a sustainable and environmentally friendly approach for antibiotic removal, particularly in contexts where minimizing chemical usage and promoting biological solutions are priorities.

3. Conclusion

The efficacy of the MCDM approach in systematically selecting the optimal method for antibiotic removal from wastewater is evident. By quantitatively evaluating biological and non-biological treatment methods based on critical criteria—removal efficiency, processing time, and COD removal efficiency—the PROMETHEE analysis identified AOPs (Photo-Fenton) as the superior chemical and physical method for amoxicillin removal, achieving complete pollutant elimination (100% removal efficiency), a rapid processing time of just 30 minutes, and a COD removal efficiency of 66%.

Among biological methods, fungal biodegradation emerged as the top-performing alternative, demonstrating a respectable amoxicillin removal efficiency of 49%, a moderate processing time of four days, and a high COD removal efficiency of 85.58%. These results highlight that while chemical methods like Photo-Fenton offer swift and highly effective pollutant removal, biological approaches such as fungal biodegradation contribute significant advantages in terms of sustainability and organic load reduction, albeit with longer treatment durations.

The potential of hybrid treatment systems is thus underscored, offering opportunities to combine the rapid efficiency of chemical methods with the environmental benefits of biological processes to overcome individual limitations and enhance overall treatment efficacy. Future research should focus on optimizing operational parameters, reducing costs, and exploring synergies between chemical, physical, and biological techniques. Implementing the MCDM framework in wastewater management can facilitate data-driven decision-making, align treatment strategies with regulatory standards, and promote sustainable and effective antibiotic removal solutions.

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SOLUTION FOR URBAN SUSTAINABILITY: A COLLABORATIVE APPROACH FOR DISASTER MANAGEMENT AND COMMUNITY AWARENESS

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Abstract: Natural disasters have increased in recent years, causing devastation to both human and natural systems. In this setting, catastrophe management has emerged as a prominent topic in recent years. Traditional methods of disaster management fail to deliver timely, relevant, and accessible information. This research focuses on the evaluation and expert validation of developed AI-based chatbot systems for disaster management. The research is part of a collaborative effort between academia and industry to use AI technology to enhance catastrophe preparedness. This work builds a context-specific chatbot to automate information distribution and connect communities, specifically addressing the special needs of landslide-prone areas in Sri Lanka. Then, several rounds of expert evaluation and public evaluation were carried out to assess the chatbot's performance, particularly to assess the user understandability, comprehensiveness of its responses, relevance, and accuracy, to highlight the importance of university-industrial collaboration. Fourteen specialists representing disciplines such as town planning, geology, geotechnical engineering, civil engineering, and architecture were used to assess the performance. Repeated revisions have been conducted based on the feedback received earlier. According to the findings, relevance demonstrated a steady enhancement, beginning at a score of 5 and reaching a maximum of 10 by the fourth round. Understandability improved consistently, achieving a perfect score of 10. Accuracy increased significantly from 5 in Round 1 to 10 in the final round, attributed to the integration of verified information. Comprehensiveness exhibited gradual enhancements, also reaching a perfect score of 10, owing to the incorporation of more detailed and example-based content. This also highlights the importance of up-to-date information and more detailed and scenario-specific chatbot responses. This work demonstrates the significant role of university-industry collaboration to enhance disaster management solutions, foster urban resilience, and achieve sustainable development by addressing Sustainable Development Goal 11, which pertains to sustainable cities and communities, and Sustainable Development Goal 13, which focuses on climate action.

Keywords: Artificial Intelligence; Chatbot; Disaster management; Community awareness; University industrial collaboration; Sustainable development

1.Introduction

Communities worldwide are experiencing a concerning rise in dangers. The frequency and severity of catastrophes, such as floods, wildfires, and storms, have markedly increased, posing a considerable hazard to numerous places globally (Parry et al., 2007). The citizens of Sri Lanka confront escalating challenges due to a rise in natural disasters, primarily landslides and floods, which interrupt daily operations, risk human life, and result in significant economic losses. Landslides occur in 10 administrative districts, encompassing around 30% of the nation's land area. During crises, Sri Lankan communities are typically inadequately prepared due to conventional disaster management strategies that rely heavily on hierarchical communication networks (Fernando, 2020).

The area of Disaster Risk Reduction (DRR) is facing increasing complexities in its efforts to mitigate and respond to increasing risks, compounded by challenges: including different types of hazards create new problems that necessitate the use of tailored and adaptable risk reduction methodologies, the geographical scope of disaster risk reduction (DRR) is further exacerbated by the availability and diversity of data sources. The need for current and accurate data cannot be overstated – it is required for effective risk analysis, creation of early warning devices, deployment planning, and execution. However, the collection, synthesis, and interpretation of information from various sources constitute enormous planning challenges, and the geographical and administrative diversity of regions also complicates disaster risk reduction measures. Different regions have varying socio-economic and cultural characteristics and have different governance and regulatory regimes, which may negatively affect the success of disaster risk reduction measures (Grafton et al., 2019).

Notwithstanding these phenomenological issues, Artificial Intelligence (AI), especially via chatbot technology, presents a feasible solution to rectify shortcomings in Sri Lanka's disaster management system. Chatbots are computer programs engineered to replicate human conversation during interactions with individuals. Chatbots are frequently employed in customer service situations, while their applicability transcends this field to encompass a variety of uses, including sustainable urban planning (Shawar & Atwell, 2007). In urban planning, chatbots can perform several tasks, including providing information to the public and promoting citizen involvement. Improving the efficiency and efficacy of planning processes (Adamopoulou & Moussiades, 2020).

The integration of AI chatbots in planning processes presents a substantial opportunity to enhance the efficiency, responsiveness, and inclusivity of municipal management. The main advantage lies in delivering real-time data and actionable insights, which enable swift and informed decision-making for planners and decision-makers. AI chatbots are capable of analyzing real-time traffic trends and identifying potential congestion areas, enabling dynamic adjustments to traffic signals or public transportation schedules to improve mobility (Wang & Biljecki, 2022). Additionally, chatbots serve as effective tools for collecting community feedback, allowing planners to engage directly with citizens on issues such as transportation needs, satisfaction with public amenities, and safety concerns (Herath & Mittal, 2022). Chatbots enhance communication and data analysis while automating tasks, including the management of municipal service inquiries, permit processing, and appointment coordination. The emerging application of AI suggests that chatbots could significantly influence disaster mitigation in the future.

Despite the shown efficacy of AI in disaster communication, there is an absence of localized, real-time chatbot systems for specific hazards such as landslides, especially in low-resource, hazard-prone areas like Sri Lanka. Therefore, this study produces an AI chatbot for landslide awareness, offering timely, localized, and actionable guidance to users, in contrast to traditional information channels that may experience delays in dissemination or limited accessibility. This research seeks to develop and evaluate an AI-driven chatbot tailored for landslide disaster management in Sri Lanka. The project will first develop a subject- and context-specific AI chatbot for landslide disaster management in Sri Lanka,

followed by an evaluation of its effectiveness with disaster management specialists and community members in the next phase.

2.Literature review

Conventional methods of disaster communication typically depend on hierarchical, top-down frameworks. Disaster communication operations rely on systematic methods, such as public media notifications, extensive broadcasts, and community gatherings. Despite the importance of these channels, they often encounter challenges in providing timely, precise, and accurate information, especially in rural or disaster-affected areas with insufficient infrastructure (Fernando, 2020). These constraints underscore the need for more dynamic, real-time communication channels to improve disaster preparedness and response.

Recent publications emphasize the importance of Artificial Intelligence (AI) tools, including chatbots, in improving disaster management through enhanced information flow coordination and community engagement, thus facilitating quicker response times. Artificial intelligence is widely utilized in multiple fields, such as transportation and land use modeling, emergency management, and related subjects. Chatbots can be primarily classified based on their specific functions, including the operation of rule-based bots, which are derived from a core set of predetermined guidelines (Goralski & Tan, 2020). Although they may not possess a comprehensive understanding, they demonstrate competence in executing essential tasks, such as disseminating information and handling basic inquiries (Relich, 2023). Furthermore, AI chatbots are increasingly evolving into advanced counterparts. These entities, enabled by AI, demonstrate the capacity to learn and adapt their behavior based on environmental stimuli. Automated systems possess the ability to understand and analyze human language, facilitating engagement in intricate and subtle conversations (Yigitcanlar et al., 2020). Individuals enhance their performance over time through diverse interactions, leading to increased proficiency in managing complex tasks, including the analysis of urban informatics. While the development and maintenance of these solutions involve increased costs, they provide enhanced effectiveness in tackling complex situations.

Also, artificial intelligence has the potential to tackle significant urban challenges that cities encounter, including traffic congestion, air pollution, and climate change (Peng et al., 2023). The ongoing development of AI technology is expected to result in more innovative and effective chatbot applications, thereby improving the efficiency of planning processes (Herath & Mittal, 2022; Kooli, 2023). This bidirectional communication ability fosters trust and promotes public engagement. In disaster preparedness, participatory characteristics are essential for ensuring that response methods are inclusive and rooted in local realities. Chatbots can alleviate cognitive burden on users by distilling technical information and presenting it in an approachable, conversational manner.

Xue et al. (2023) investigate the role of chatbots in disseminating real-time information for natural disaster avoidance, emphasizing their effectiveness in enhancing public awareness. Chatbots provide an effective means for the prompt and direct distribution of critical information through localized and context-specific notifications. Xue et al. (2023) argue that chatbots can function on low-connectivity platforms, thus increasing their utility in remote or underserved regions with restricted internet access. This versatility is essential in situations where challenges in digital infrastructure may impede swift communication, as evidenced in Sri Lanka.

However, specific challenges persist concerning the current implementations. The ERMES chatbot effectively provides instructions and updates in emergencies; however, it does not possess the ability to incorporate user feedback. This limitation obstructs the creation of a dynamic feedback loop and the capacity to adjust fundamental assumptions as new data becomes available over time (Urbanelli et al., 2024). This deficiency suggests that chatbots operate merely as passive tools instead of active participants in disaster management, underscoring the necessity for improvements in their bidirectional

capabilities. A significant number of studies focus on the use of chatbot technology in developed countries, while there is a scarcity of research exploring its potential in developing economies that face diverse infrastructural and socio-economic challenges. Additionally, there is a lack of research on the adaptation of chatbot frameworks to tackle specific geographic hazards, such as landslides and flooding, which are common in Sri Lanka. This highlights a research gap and presents an opportunity to create a chatbot designed for the distinct needs of disaster-affected populations, providing a valuable case study for other regions encountering similar challenges. The role of chatbots in disaster management is clear; nonetheless, current literature indicates significant gaps that necessitate further investigation.

In summary, although AI chatbots demonstrate potential in improving catastrophe communication, substantial deficiencies persist regarding localization, bidirectional engagement, and contextual relevance. This research mitigates these constraints by creating a chatbot tailored for landslide-prone areas in Sri Lanka. The chatbot incorporates expert feedback, iterative enhancement, and specialized data to deliver real-time, user-focused disaster information. This study addresses a need in the field of AI-enabled catastrophe risk reduction and promotes the progress of Sustainable Development Goals pertaining to resilience, innovation, and community participation.

3. Materials and Methods

3.1 Chatbot Development Framework

The chatbot's development followed an iterative and modular architecture, aimed at ensuring contextual relevance, technical robustness, and user-centered design. The initial phase of Chatbot development involved the collection and processing of necessary data. Disaster-related data, primarily comprising planning guidelines, public awareness materials, and technical reports obtained in PDF format from authoritative sources such as the National Building Research Organisation (NBRO), formed the knowledge base of the chatbot. All data utilized in this study were obtained from publicly accessible documents or supplied with explicit consent. This data selection aimed to ensure that chatbot responses remained precise and contextually relevant to disaster management needs. The phases of chatbot development included the configuration of the environment, integration and management of PDF documents, initialization of the language model, and development of conversational functions.

The development environment was established with Python, incorporating the Falcon-7B-Instruct language model through Hugging Face's transformers library. Hyperparameters consisted of a learning rate, a batch size of 4 with gradient accumulation, epochs, and bfloat precision. The chatbot's backend architecture had elements for content parsing, embedding generation, and natural language query processing. Documents were transformed into text and vectorized with Sentence-BERT embeddings. A comprehensive pre-processing pipeline was implemented to ensure high data quality. Texts were divided into manageable segments (tokens). The chatbot's interface was created with a straightforward graphical user interface (GUI) that facilitates real-time input and feedback. Temperature settings were modified to 0.2 and 0.9 to evaluate consistency and inventiveness in answers. 6 models were created as shown in Table 01. Despite the computational intensity of full-scale fine-tuning for Falcon-7B-Instruct, quick engineering and retrieval-augmented generation (RAG) approaches were employed to improve performance. Figure 1 illustrates the chatbot development methodology employed in this study. Initial data-enabled model training, while insights from expert and public evaluations informed later refinement iterations. The image depicts the relationship between development, testing, GUI configuration, and validation within a continuous improvement framework.

3.2 Evaluation Methodology

The chatbot underwent four phases of expert evaluation. Fourteen experts from diverse disciplines, including urban planning, geology, geotechnical engineering, civil engineering, and architecture, participated in the study, comprising six from NBRO and eight external contributors. The evaluation benchmarks included:

- Relevance — the extent to which responses aligned with disaster-related inquiries.
- Comprehensibility — the clarity and accessibility of content.
- Accuracy denotes the precision of both technical and localized information.
- Comprehensiveness - thoroughness and contextual integrity.

The evaluation was performed in four rounds. In each iteration, expert feedback guided enhancements to the model prompts, content repository, and graphical user interface components. A Likert scale ranging from 1 to 10 was employed to measure performance. To mitigate bias, the sequence of queries was randomized for each evaluator and round. Input from each iteration was utilized to progressively enhance prompt formulation, domain comprehensiveness, and interface lucidity.

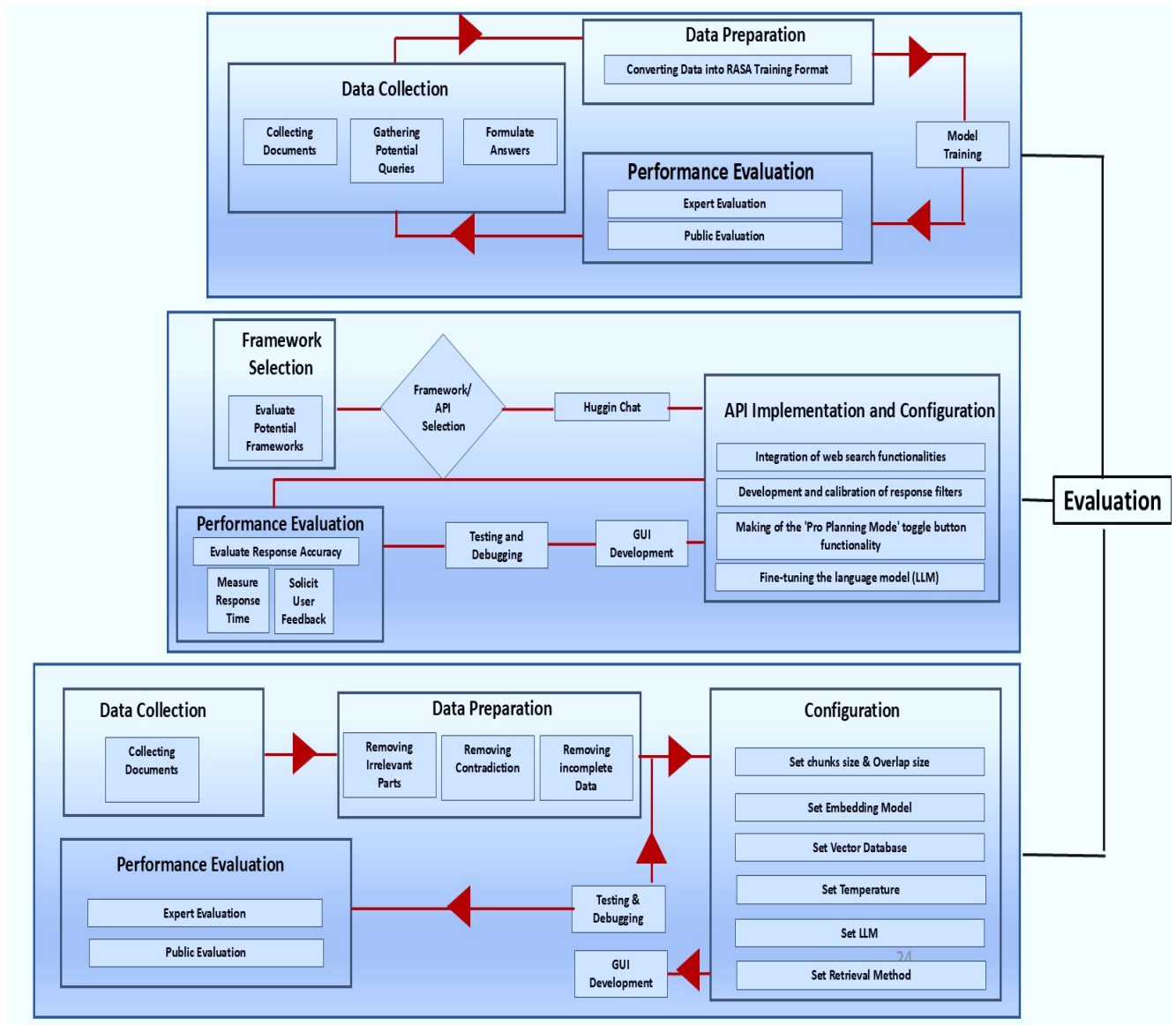


Figure 01: Methodology of chatbot development

Table 01: Comparison of 6 models.

Chatbot	Description	Temperature
llama2_7b	A general-purpose LLM with 7 billion parameters, trained on a massive dataset for broad language understanding and generation. It can handle tasks like summarization, translation, and code creation. But, it's not specifically designed for anything.	1 0.2 (More predictable and controlled responses)
		2 0.9 (More creative and diverse responses, but potentially less reliable)
TheBloke/Llama-2-7B-Chat-GGML	Fine-tuned for conversation. It's the same 7-billion-parameter Llama 2 model but fine-tuned for chat. It understands conversational cues, engages in open-ended dialogue, and adapts to how the conversation flows.	3 0.2 (More predictable and controlled responses)
		4 0.9 (More creative and diverse responses, but potentially less reliable)
falcon-7b-instruct	An open-source Large Language Model (LLM) built by TII. Fine-tuned for both chat and instruction tasks. Developed on the strong foundation of the Falcon-7B model, tiiaae-falcon-7b-instruct comes ready-to-use for basic conversational interactions and completing tasks as instructed.	5 0.2 (More predictable and controlled responses)
		6 0.9 (More creative and diverse responses, but potentially less reliable)

4.Results

4.1 Chatbot Development

LANDSLIDE AWARENESS CHATBOT

Ask me anything related to landslides!

Textbox

what are landslide prone districts

Clear

Submit

output 0

Helpful Answer: The following are some districts in Sri Lanka which are landslide prone:
10. Badulla, Galle, Hambantota, Kalutara, Kandy, Kegalle, Matale, Matara, Nuwara Eliya, and Ratnapura
The districts are designated as landslide prone by the National Building Research Organization (NBRO).

References:
Use the following pieces of context to answer the question at the end. If you don't know the answer, just say that you don't know, don't try to make up an answer.

"These maps indicate areas prone to slope failures and should be referred to before selecting a site for construction.",
(c) Areas with Previous Landslide Activity",
"Avoid building in areas where landslides have occurred.
Indicators of previous landslides include:",
"Irregular topography.",
"Disruption of vegetation.",
(b) Areas Designated Unsafe",

Figure 2: Chatbot interface

This section presents the key outcomes of the chatbot development and evaluation process. Figures 2 illustrate the chatbot interface during the development phase. It presents the initial prototype, featuring a basic input-output layout focused on verifying core retrieval functionality.

4.2 Chatbot Evaluation

During the performance evaluation phase, crucial qualitative and quantitative indicators were utilized to evaluate the effectiveness of the chatbot in regard to responding to requests concerning disaster management. A continuous feedback loop was incorporated into this process. It was launched by expert reviews and user testing, and it was followed by enhancements that were influenced by the literature, modifications to the algorithm, and upgrades to the user interface. By utilizing this iterative cycle as the development of the chatbot was ensured to agree with the expectations of stakeholders and the best practices in the field of technology.

During the evaluation process, a mean effectiveness score was produced for each of the four key assessment criteria, which were information relevancy, user comprehensibility, data accuracy, and comprehensiveness. This score ranged from one to ten, and it was used to determine how effective each chatbot model was. Based on these criteria, Figure 3 provides a comparative study of all six chatbot models, with error bars reflecting the standard deviation of each model. Importantly, NBRO BOT Temp 0.2 (falcon-7b-instruct) demonstrated greater performance in terms of user comprehensibility and user understandability, either matching or surpassing the performance of global models such as ChatGPT 4.0 and Google Gemini. A benchmark was developed through this early study, which will serve as a guide for future enhancements.

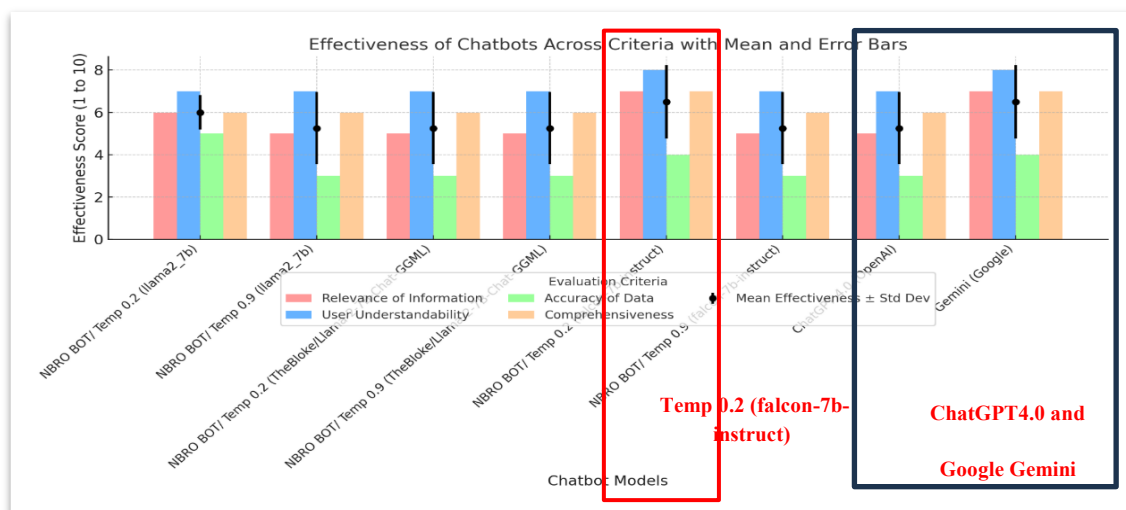


Figure 03: Comparison of six chatbot models

Following Figure 4, a circular graphic is used to illustrate how different NBRO chatbot parameters affect the operation of the chatbot. It highlights robust first performance in user comprehensibility and thorough responses while showing moderate early performance in accuracy and relevance that subsequently improved through feedback and model improvement. In addition, it emphasizes rigorous beginning performance in correctness and relevance. A visual representation of the accuracy scores for each model is provided in Figure 5. It is clear that Falcon-7B had a performance that was initially below average; however, further improvements, such as the addition of content that was specific to a domain, helped to close the gap between the two. This provides more evidence that the decision to improve training data and adjust model cues was a strategic one. These figures, when taken as a whole, provide quantitative benchmarks and diagnostic insights that demonstrate the need for incremental improvements to be made to the chatbot solution.

When compared to all other chatbots, Temp 0.2 (falcon-7b-instruct) had the most substantial gains across all categories. It achieved remarkable scores as a result of targeted enhancements and dataset customization. Other chatbots, on the other hand, demonstrated consistent development but continued to achieve lower levels of effectiveness in crucial areas like as accuracy and comprehensiveness. Development through iterative processes and feedback from specialists was the primary driver that drove performance improvements. Figure 7 shows the Performance Improvements of Chatbots.

- Relevance - Demonstrated consistent improvement, beginning with a score of five and reaching a perfect score of ten by the fourth round.
- User Understandability - Made steady progress, attaining a perfect score of ten in the acceptable level by addressing input on simplifying technical words for users who are not experts.
- Accuracy increased significantly from five in the first round to ten in the final round.
- Comprehensiveness - Gradual improvements were seen, with NBRO BOT/Temp 0.2 (falcon-7b-instruct) achieving a perfect 10 due to the introduction of more detailed and example-based content. This was because the content was more comprehensive.

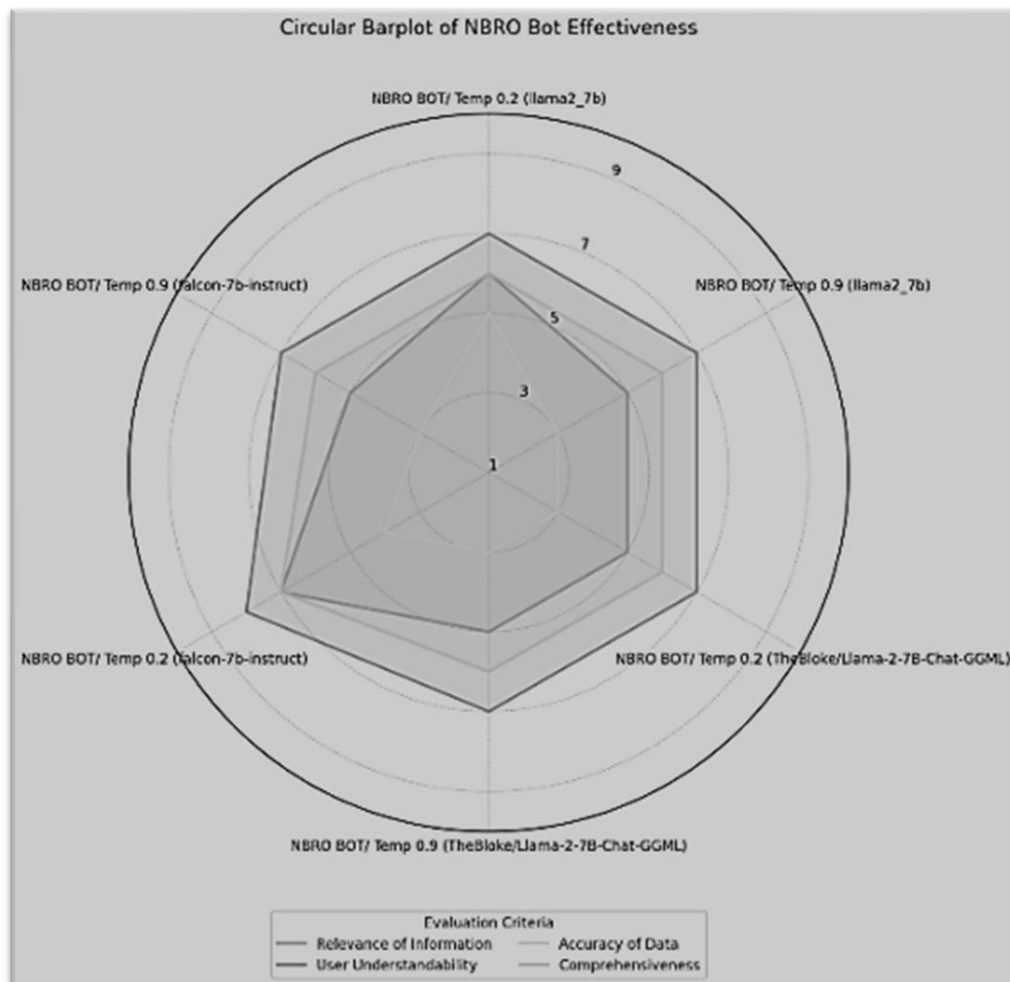


Figure 05: Circular diagram

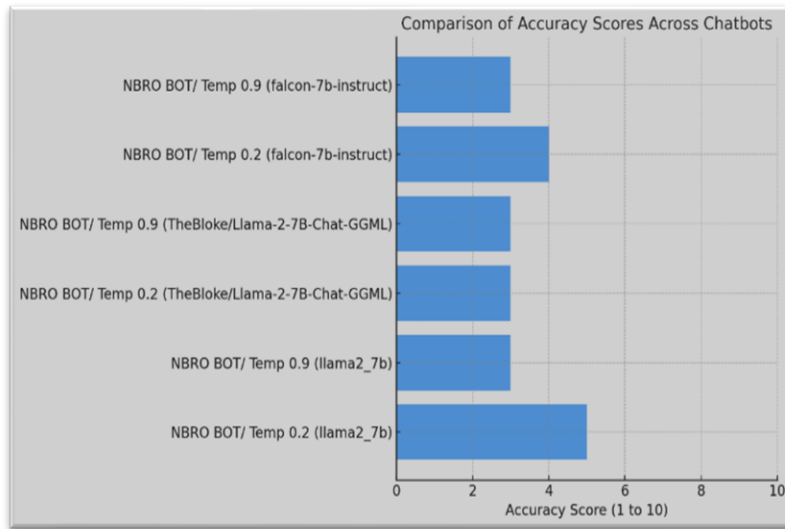


Figure 06: Accuracy scores for all models

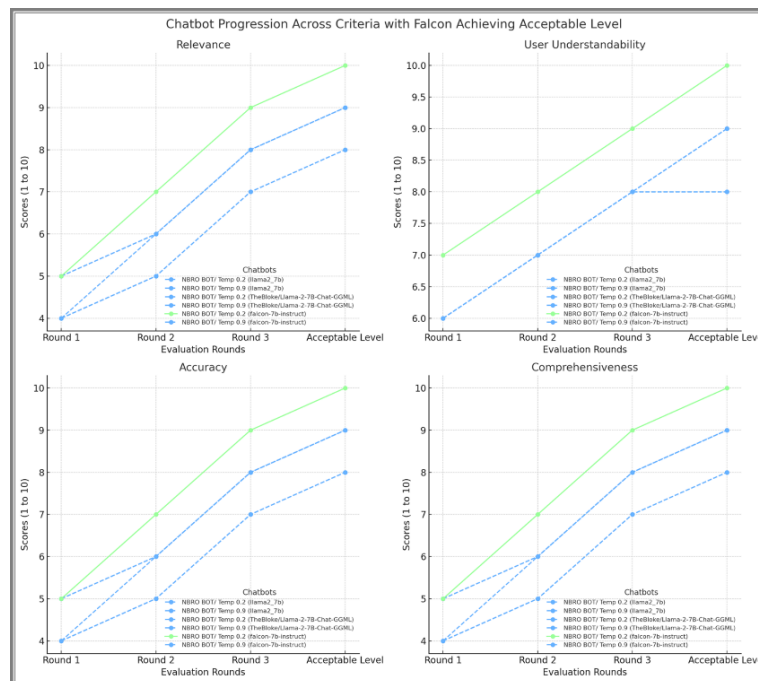


Figure 07 : Performance Improvements of Chatbots based on Each Phase of Development

5. Discussion

Based on the findings of Caragliu et al. (2011) and Yigitcanlar et al. (2021), the implementation of artificial intelligence in sustainable planning results in a significant enhancement of public participation, information dissemination, and decision-making that is driven by data. A demonstration of how artificial intelligence has the potential to improve the effectiveness and inclusiveness of decision-making processes is provided by the transition to a chatbot that is equipped with advanced technologies such as the Hugging Chat API and real-time web search. The chatbot has not been deployed in a live disaster event; however, the iterative expert evaluation simulates practical usage conditions. Experts from the National Building Research Organization and local planning authorities assessed the tool's relevance and usability within the context of landslides in Sri Lanka. The findings of this study shed light on an essential change that is required in the frameworks that govern disaster preparation and response. Conventional approaches, such as written warnings, loudspeaker announcements, and delayed alerts, are fundamentally generic, devoid of contextual sensitivity, and do not foster two-way contact. It is important to note that these methods are not effective in improving communication. A loop of public inexperience, mistrust, and vulnerability is maintained as a result of this communication deficit

during times of emergency. Through the implementation of a communication system that is instantaneous, localized, user-centric, and encourages trust, this deficit can be mitigated through the iterative design of a context-specific AI-driven chatbot. It was guaranteed that the chatbot would apply to the parts of Sri Lanka that are prone to natural disasters.

A synergistic relationship between the university and industry was the driving force behind this transformation. This collaboration strategically integrated academic competence with technological innovation. The University was the driving force behind the diagnosis of the issue, the collection of data, and the evaluation of the model in order to ensure that it was relevant to the community and the context in which it was being applied. The establishment of a basis for real-time, scalable deployment and iterative enhancements was made possible by the considerable contributions made by industry partners. These contributions included the provision of sophisticated infrastructure, the deployment of the Falcon-7B-Instruct model, and the development of a chatbot interface that was accommodating to users' needs. This relationship resulted in a high-performing prototype that consistently outperformed the capabilities of leading models such as ChatGPT 4.0 and Gemini. This was especially true in terms of the user's capacity to grasp the model and the nuanced, scenario-based responses it provided. The findings indicate the greater potential of co-developed, locally verified artificial intelligence solutions in comparison to generic techniques.

To summarize, the effort that has been presented directly addresses Sustainable Development Goal 11 by improving the safety and resilience of cities. Due to the fact that it encourages innovation in catastrophe planning, it is also relevant to Sustainable Development Goal 9. Additionally, the development of a chatbot application for participatory disaster awareness and early warning, with a particular emphasis on landslides, aligns with Sustainable Development Goal 13. Additionally, it aligns with Sustainable Development Goal 17 (Partnerships for the Goals) by demonstrating the efficacy of university-industry collaborations for sustainable innovation.

1. Conclusion

This research introduces a novel conversational system that facilitates rapid and effective bidirectional communication, integrating a variety of straightforward yet powerful functionalities for landslide management. The solution enables collaboration among stakeholders, such as decision-making agencies, control center technicians, field personnel, and residents, for the exchange of essential information. The originality of this study lies in the proposed technology, which synthesizes concepts from prior research on mobile applications and chatbots aimed at disaster risk reduction (DRR).

By demonstrating that artificial intelligence technology, when informed by expert knowledge and collaborative stakeholder involvement, has the potential to effectively overcome communication gaps in catastrophe risk management, this study serves as evidence. With this chatbot model, a baseline is established for later AI implementations in areas that are considered to be in danger. This exemplifies the potential for co-creation between the academic world and the business world to speed up the development of solutions that are both practical and scalable, and that are in line with the Sustainable Development Goals.

2. Limitations and Future Works

The chatbot system was found to have limitations, despite the fact that it displayed extremely high performance. The chatbot that was built cannot explore photographs, comprehend geo-referenced locations, or comprehend facts related to maps. Consequently, it is incapable of comprehending or recognizing any visuals that it encounters. Even though they are able to interpret literal English, chatbots usually struggle to comprehend the contextual nuances of specific questions. Future initiatives must focus on the integration of memory modules, enhancement of image and map comprehension, expansion of training utilizing domain-specific datasets, incorporation of bias mitigation techniques, and optimization of cost-effective deployment strategies to maximize the chatbot's potential.

Acknowledgment

The authors gratefully acknowledge the contributions of the National Building Research Organisation (NBRO), supporting industry partners, and the 14 experts who contributed to the refinement of the chatbot system. And acknowledge the support of Dr. Nuwan Dias, Lecturer in Disaster Management at the University of Manchester, for providing funding for the development of the chatbot.

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INNOVATIVE APPROACHES TO SUSTAINABLE FOOD PRODUCT DEVELOPMENT

ICSD 094

DETERMINATION OF THE KNOWLEDGE, ATTITUDES, AND UTILIZATION OF COOKING OIL AMONG FAMILIES OF APPLIED SCIENCES UNDERGRADUATE STUDENTS IN A SELECTED UNIVERSITY, SRI LANKA**S. A. K. S. Subasingha¹, Renuka Jayatissa², P.G.S.M. De Silva³, A. Buddhika G. Silva^{2*}**¹*Department of Botany, University of Sri Jayewardenepura, Nugegoda 10250, Sri Lanka.*²*Department of Nutrition, Medical Research Institute, Colombo 00800, Sri Lanka.*³*Department of Electron Microscopy, Medical Research Institute, Colombo 00800, Sri Lanka.***Correspondence E-mail: buddhikagayani@yahoo.com, TP. +94112693533*

Abstract: Dietary fats are essential components in human nutrition. Worldwide, people commonly use cooking oil as a source of dietary fats for food preparation and processing. Recent studies have raised concerns regarding the association between cooking oil consumption and the risk of cardiovascular diseases, several types of cancers, and neurological disorders. To improve the understanding of this phenomenon, we need to know about the culinary oil consumption patterns of different communities. This study aimed to obtain details about the knowledge, attitudes, and practices related to cooking oil use and determine the daily cooking oil usage among undergraduate students and their families in the Faculty of Applied Sciences at a selected university. The analyzed results showed that the undergraduates and their families have adequate knowledge, attitude, and cooking practices about cooking oil, and the average daily cooking oil consumption per individual was approximately one tablespoon (15 g).

Keywords: Cardiovascular diseases; Cooking oil; Dietary fats

1. Introduction

Dietary fats are water-insoluble organic elements, primarily composed of triacylglycerol compounds, and esters formed from glycerol and fatty acids. These fats are generally classified into two categories: solid fats and liquid fats, depending on their melting points (Lawrence, 2013; Saini, 2017). Among dietary fats, vegetable oils are the most used and economically accessible source.

Increasing consideration has been given to the nutritional quality of fats and oils due to their strong association with diseases of the circulatory and nervous systems (Orsavová et al., 2015). According to the World Health Organization (WHO, 2017), 17.7 million deaths globally in 2015 were attributed to cardiovascular diseases, a number projected to rise to 23.3 million in the coming years. Consequently, the dietary intake of fats and oils has become a major public health concern.

The nutritional value of edible oils is determined by several factors, including their fatty acid profiles, the degree of unsaturation, and the structural framework of fatty acids within triglycerides (Dhyani et al., 2018). Several clinical and animal studies have shown that saturated fats contribute to raised blood and plasma cholesterol levels, while monounsaturated and polyunsaturated fats help reduce these levels (Lawrence, 2013). However, oils rich in unsaturated fatty acids are more prone to oxidation and thus less stable during storage and cooking. The expansion of oils that are both nutritionally beneficial and stable under various conditions remains a challenge, predominantly in the context of modern dietary and lifestyle changes.

This study aims to assess the knowledge, attitudes, and cooking practices related to oil consumption among undergraduate students and their families at the Faculty of Applied Sciences, in a selected university in Sri Lanka. It also seeks to analyze the average daily per capita cooking oil consumption within this population.

Given the probable health risks associated with excessive consumption of saturated fats and cooking oils, this research further aims to raise consciousness among university students and their families about non-communicable diseases linked to poor dietary fat choices. Encouraging a reduction in oil intake and the consumption of deep-fried foods; both at the household level and in the food industry, is essential for fostering healthier dietary habits. The acquisition of proper knowledge, accompanied by positive shifts in attitudes and behavior, is vital for adopting and maintaining healthy food practices both within families and the wider community.

2. Materials and Methods

2.1 Questionnaire survey

As the survey population, undergraduate students in the Faculty of Applied Sciences at a selected University in Sri Lanka and their families were selected. The desired sample size for the questionnaire-based survey and 24-hour recall was estimated by Andrew Fisher's Formula (Fisher, L. D, 1998). A specific Stratified random sampling method was used for the selection of 385 sample sizes from the responses to the survey. Considering a 30% non-respondent rate, the questionnaire was given to 550 participants. This adjustment is based on prior similar studies involving survey distribution among university students and general populations, where non-response rates typically range from 20% to 40% (Gomm, 2008).

A pilot study was conducted with a randomly selected subset of 100 undergraduate students and their families from the same faculty. The pilot study intended to test the clarity, reliability, and feasibility of the questionnaire, as well as to find any possible issues in data collection procedures. Based on the results and feedback from the pilot phase, required revisions were made to improve the final questionnaire and study etiquette. The main cross-sectional descriptive study was then implemented using the revised apparatuses to collect data from the full sample of 550 contestants.

Design the questionnaire survey.

In the pilot study, data on daily cooking oil practice were collected through a seven-day dietary diary maintained by respondents. Participants were educated to estimate the amount of oil used in meal

preparation and record it daily. Comprehensive written guidelines were provided to ensure uniformity and precision in recording, including examples of common household measurements (e.g., teaspoons, tablespoons, milliliters) and typical serving sizes. The diary was self-reported.

For the main survey, data were gathered on participants' average daily and weekly cooking oil consumption using a self-administered online questionnaire. The inquiry form was designed to approach a wide range of information, including the frequency, types of cooking oils used, the type of fried food consumption, and the cooking methods commonly practiced by the participants. The questionnaire included a mixture of multiple-choice questions, Likert scale items, and open-ended questions (to detente additional insights on oil usage habits).

Ethical approval for the study was obtained from the Ethical Review Committee of the Faculty of Medicine, University of Sri Jayewardenepura. Participation was voluntary, and informed consent was obtained electronically from all respondents prior to data collection.

Data collection

After responding to the Google form, all the information was collected into Google Sheets. All the data has been stored in a password-protected folder.

Inclusion criteria

- Undergraduates of the Faculty of Applied Sciences, in a selected University, who have given consent to participate in the study.
- Family members of undergraduates of the faculty of Applied Sciences, in a selected University, who have given consent to participate in the study.

Exclusion criteria

- People who are not undergraduates of the faculty of Applied Sciences at a selected University.
- Students of the faculty of Applied Sciences, in a selected University, who did not give consent to participate in the study.
- Students of the faculty of Applied Sciences, in a selected University who stay away from their families.

Data analysis

All collected data were entered into Microsoft Excel for initial cleaning and organization. For each household, the total volume of cooking oil used per day was calculated based on self-reported values. To estimate weekly consumption, daily values were totaled over a seven-day period. To determine average oil consumption per person, the total household oil intake was divided by the number of family members reported by each participant. It was assumed that oil consumption was distributed equally among all family members unless otherwise specified. Households with incomplete or inconsistent entries (e.g., missing family size, implausibly high or low oil use) were carefully reviewed, and obvious outliers were excluded from the final analysis based on predetermined criteria (e.g., ± 3 SD from the mean). A standard tablespoon (15 mL) was used as the conversion unit for all oil volume estimations, as specified in the instructions given to participants. Statistical analysis was conducted using IBM SPSS Statistics 27.0. The following tests were applied based on data type and research objectives. Descriptive statistics were presented as mean $\pm$ standard deviation (SD), 95% confidence intervals (CI), medians, or percentages, depending on the distribution and nature of the data. A two-tailed p-value < 0.05 was considered statistically significant for all analyses.

3. Results and Discussion

A total of 385 undergraduate students from the Faculty of Applied Sciences at a selected university, along with their family members, participated in the present cross-sectional online survey. The survey was designed to assess dietary fat consumption patterns and related knowledge, attitudes, and practices among this population cluster.

In terms of gender distribution, a significant mainstream of the respondents was female, accounting for 65.2% (n = 186) of the total sample, while males represented 34.8% (n = 99). This female predominance may reflect either a higher proportion of female students in the faculty or a greater willingness among female participants to be involved in health-related surveys, a pattern that has been correspondingly reported in other studies (Gokhale, N, 2005). Such gender imbalances are important to acknowledge, as they may influence dietary choices and health behaviors, which frequently differ between males and females.

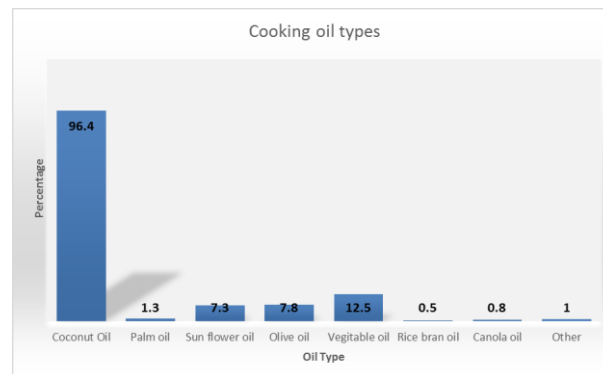


Figure 1: Cooking oil types

To assess the prevalent types of cooking oils used by the study population, eight different oil types were included in the analysis: coconut oil, palm oil, sunflower oil, olive oil, vegetable oil, rice bran oil, canola oil, and other unspecified oils. As demonstrated in Figure 1.0, coconut oil was devastatingly the most used culinary oil, reported by 96.4% of the respondents. This leading preference is reliable with long-standing culinary traditions in Sri Lanka, where coconut oil has been a staple in household cooking due to its availability, flavor profile, and cultural acceptance. (Jayawardena *et al.*, 2021)

The following, most commonly used oil type was unspecified, labeled as vegetable oil, with 12.5% of members indicating its use. This may replicate its availability in urban supermarkets and marketing as a general-purpose, neutral-tasting oil. Sunflower oil (7.3%) and olive oil (7.8%) showed comparable usage rates, signifying a growing awareness among certain groups, possibly those with higher health consciousness, of these oils' reputed cardiovascular benefits. (Gamage, Pathirage and Samarakoon, 2023)

In contrast, palm oil (1.3%), rice bran oil (0.5%), and canola oil (0.8%) were hardly used. These low rates may be due to higher costs, limited market availability, or a lack of familiarity within the local population. A small proportion (1%) reported using other types of oils, which may include specialty or blended oils not listed in the primary categories.

These findings diverge notably from consumption trends observed in other countries. For example, in a study conducted in India (Gokhale, 2005), a higher quantity of respondents reported using soybean oil and sunflower oil as main cooking mediums. Equally, Govindaraj *et al.* (2012) found that in Tamil Nadu, coconut oil accounted for only 4–9% of household oil usage. These regional differences highlight the significant impact of cultural dietary patterns, local agricultural production, economic thoughts, and health perceptions on customer behavior related to cooking oil selection.

The predominance of coconut oil in this study suggests a need for public health awareness around its saturated fat content, particularly in the context of non-communicable disease (NCD) prevention. At the same time, interventions promoting the variation of healthy unsaturated fats may need to consider sensory acceptability and affordability when recommending dietary changes.

Participants reported using both loose and branded oils, with 79% choosing loose oil due to its affordability. This finding is important as the quality and safety of loose oils may not be standardized

or supervised as rigorously as branded oils. Understanding this preference highlights the need for food safety regulations and awareness operations on the risks of using unregulated cooking oil.

To estimate the quantity of cooking oil used by households on a regular basis, participants were asked to report their average weekly usage (Figure 2.0). The responses, primarily provided in liters, were standardized into common household units (e.g., 250 mL increments) to facilitate clarification and assessment.

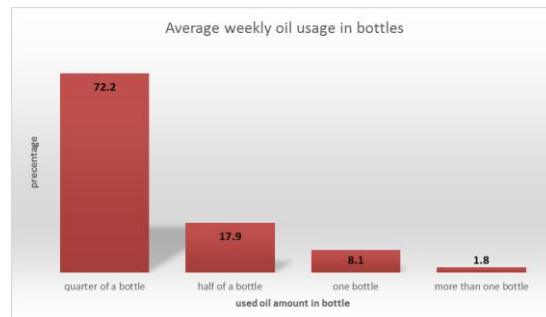


Figure 2: Average weekly oil usage in bottles

The findings revealed that most participants (72.2%) reported using approximately 250 mL of cooking oil per week. This suggests a relatively conservative oil consumption pattern among most households, potentially indicative of either small family units, unique cooking practices, or heightened consciousness regarding the health implications of excessive oil intake. Additionally, 17.9% of participants reported using 500 mL per week, while 8.1% consumed up to 1 liter per week. Notably, only 1.8% of respondents reported usage beyond 1 liter per week, indicating that extremely high-volume oil consumption is uncommon among the surveyed population. These differences in oil usage could be attributed to several manipulating factors. Family size is likely a major determinant; larger households with multiple members would naturally require greater amounts of cooking oil.

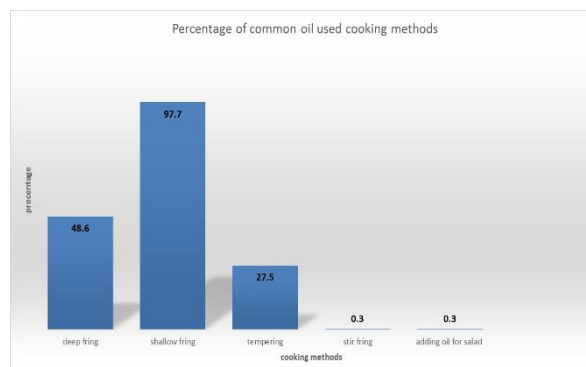


Figure 3: Percentage of common oil used cooking methods

Participants were also asked to specify the cooking methods commonly employed in their households, with a particular focus on techniques involving the use of edible oils (Figure 3.0). According to the responses, 97.7% of participants said that shallow frying was the most common technique. The next most popular methods were deep-frying (48.6%), tempering (27.5%), stir-frying, and adding oil to salads, which was only done by 0.3% of respondents. These results show a definite preference for cooking methods based on frying, which are generally linked to increased dietary fat intake and higher oil consumption. Notably, food is coated or submerged in oil during both shallow and deep frying, which can cause a substantial amount of oil to absorb into the food ingredients. These behaviors may also lead to the development of dangerous lipid oxidation products and trans fats, especially when oils are heated or reused frequently, as is common practice. The development of harmful lipid oxidation products and trans fats has been linked to several diseases, including cardiovascular disease, neurological disorders, and certain cancers.

The comparatively lower occurrence of tempering, a technique common in South Asian cuisine where oil is briefly heated with spices, indicates a more limited role of oil in flavoring associated with its role in cooking main dishes. Meanwhile, the extremely low use of oil in salads suggests that cold-pressed or unheated oil applications are rare in the dietary patterns of this population, possibly reflecting cultural preferences and the uncommon consumption of raw vegetable-based meals.

Overall, these cooking practices underline the central role of oil in heat-based culinary methods, particularly frying, within this population. Most of such methods call for targeted health involvements promoting the adoption of healthier cooking substitutions, such as steaming, grilling, boiling, or baking, which significantly decrease oil usage and the linked health risks. Educational campaigns should be arranged to make the general public aware of the proper oil usage techniques, such as avoiding repeated heating and maintaining suitable frying temperatures to mitigate the formation of harmful compounds. These discoveries align with broader public health significances focused on reducing dietary fat intake and promoting heart-healthy cooking performs, especially in populations at risk of non-communicable diseases due to lifestyle and dietary influences.

To better understand the foundation behind the widespread use of oil in cooking practices, participants were asked to indicate their reasons for choosing oil-based cooking methods (Figure 4.0). The responses exposed that taste enhancement was the most cited factor, with 92.2% of respondents representing that the use of oil significantly improves the flavor of food. This highlights the strong influence of sensory appeal, predominantly taste, on dietary behaviors and culinary preferences. In addition to taste, 38.2% of contributors noted that oil contributes to enhanced texture, such as crispiness and mouthfeel, especially in fried foods. This finding aligns with the leading use of shallow and deep-frying methods observed in the study population, both of which rely deeply on oil for desirable sensory features.

Interestingly, 17% of respondents believed that oil usage gives nutritional benefits, while 14% related it to health benefits. These responses point to the existence of misconceptions or incomplete understanding about the nutritional role of cooking oils. Although certain oils (e.g., canola oil or olive oil) do offer health-promoting properties due to their unsaturated fat content, the regular use of saturated fats like coconut oil or the reuse of oils in frying can cause health risks if not managed properly. The comparatively low percentage of participants identifying health benefits may also reflect a growing but still limited consciousness of these nutritional values.

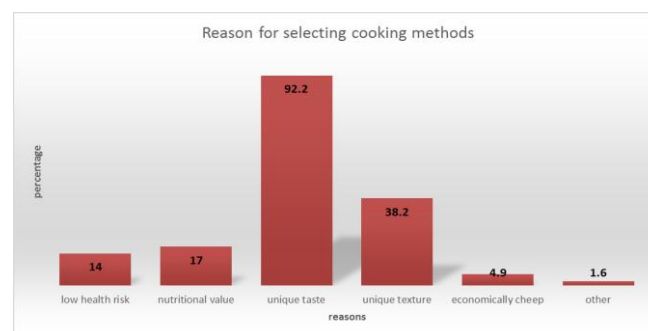


Figure 4: Reason for selecting cooking methods

Solitary 4.9% of participants cited financial considerations as a key factor in their choice of cooking method. This suggests that cost plays a relatively inconsequential role in oil usage decisions when compared to factors such as texture and flavor. Still, it may also indicate that participants are more focused on instant culinary outcomes than on long-term dietary costs or health effects. These findings reflect the cultural importance of taste and texture in meal preparation, as well as possible gaps in nutritional knowledge regarding the health implications of oil usage. This presents a valuable opportunity for targeted public health involvement and nutrition education programs aimed at endorsing informed decision-making. By encouraging people to choose healthier oils and cooking practices, such efforts could help to the reduction of diet-related chronic diseases.

Survey participants were also asked to specify the food items most frequently prepared using culinary oil. Figure 5.0 elucidates the percentage of commonly used fried food items among participants. The results showed that, a strong preference for frying protein-rich, animal-based based and vegetable-based foods. Fish was the most popular fried item, reported by 80% of respondents. This high portion reflects both the cultural dietary customs of the region where fish is a primary protein source and the suitability of frying to enhance its flavor and texture.

Subsequently, vegetables were mentioned by 73.5% of respondents, indicating that oil is commonly used even in the cooking of plant-based foods in the diet. Eggs were also typically cooked in oil, as per 57.1% of respondents, again promoting the consequences of frying practices in daily food preparation. Other often mentioned food items, such as dry fish (35.1%) and chicken (31.7%), while short-eats a term referring to fried snacks, were cited by 11.4%. Moreover, 15.6% of participants reported frying other food items, emphasizing the various applications of oil across multiple meal types and cooking methods. These usage patterns underscore the wide role of cooking oil in the preparation of both main and additional foods, mostly those rich in proteins and vital nutrients. Such practices may improve palatability, but they also raise total fat and energy intake, possibly contributing to opposing health outcomes if not balanced within the wider dietary context. This result shows that nutrient-rich foods may experience breakdown of nutrients or increased caloric density due to absorption of oil during the cooking process.

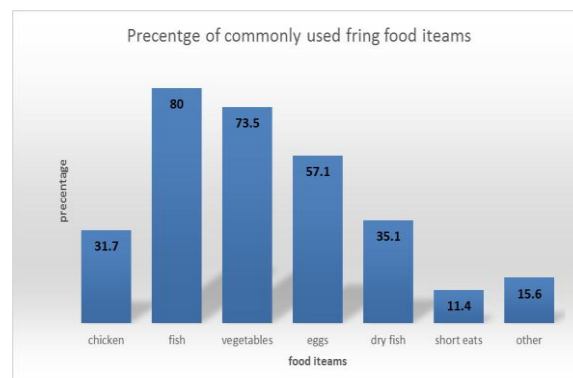


Figure 5: Percentage of commonly used fried food items

Furthermore, frying protein-rich foods like fish, chicken, and eggs frequently at high temperatures can be a reason for the formation of harmful substances such as acrylamide, heterocyclic amines (HCAs), and advanced glycation end-products (AGEs). These compounds have been connected to oxidative stress and amplified risk of chronic diseases, with cardiovascular conditions and relevant types of cancer. The findings thus support the importance of promoting healthier food preparation techniques, such as steaming, grilling, boiling, or air-frying, as replacements for conventional oil-based cooking methods. Besides, public health approaches should focus not only on the amount of oil consumed but also on the context in which it is used, mainly in relation to the frequency of frying and the types of food prepared.

Reusing cooking oil is a common practice in many households, encouraged by economic conditions and cultural factors. In this study, members were asked about their oil reuse behaviors and the incentives behind such follows. The results showed that 49.1% of participants mentioned not reusing cooking oil, representing a preference for one-time-use oil, probably reflecting improved awareness of the potential health risks linked with the oil degradation process when reheating. Equally, 31.2% of respondents deep-rooted that they do reuse an oil, whereas 19.7% chose "maybe", suggesting occasional osituational

reuse, probably influenced by the amount of oil used, the type of food cooked, or household economic considerations.

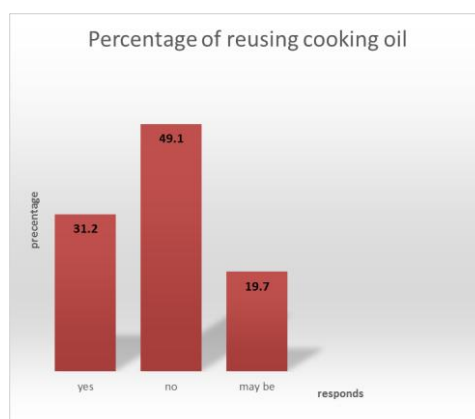


Figure 6: Percentage of reusing cooking oil

It has been recognized that the consumption of reused cooking oil causes several types of cardiovascular diseases. Figure 6.0 highlights the percentage of reusing cooking oil among participants. Among the respondents who accepted reusing oil, the primary reason (51.9%) was to reduce waste, which represents an environmentally friendly mindset and a purpose to make the most of available resources. Economic causes were cited by 19%, mostly relevant in families where the cost of oil is a significant amount in food expenses. A few numbers of respondents (3.9%) believed that recycling oil improved the flavor profile of food, which may be connected to traditional cooking practices that value residual seasoning in cooking oil. Further, 7% believed other different reasons for reuse, including accessibility or lack of awareness about potential health hazards.

When considering reuse frequency, 33.8% of those who reused oil mentioned doing so only once, representing a cautious alert likely empowered by health concerns or changes in oil quality (e.g., odor, color, and viscosity). Very few contributors reported reusing oil more than twice, signifying that repeated use is rare in this population. Significantly, 42.3% of the total sample did not respond to the question regarding reuse frequency. This non-response could rationally be credited to the participants who either do not engage in reuse practices or were hesitant about their own behaviors due to shared cooking methods or less attention to reuse frequency.

These results focus on a diversity of practices and beliefs about oil reuse. Although a majority either avoid or limit reuse, a significant minority are involved in it, primarily due to environmental or economic reasons. However, repeated heating of oil can lead to degradation in chemical composition, including the polar compounds, oxidized lipids, and trans fats formation, all of which pose health risks when consumed regularly.

This study discovered participants' fried food consumption behaviors, which were obtained from external sources, as these are a significant portion of overall dietary fat intake and possible exposure to recycled cooking oils. A notably high number of respondents (79.7%) mentioned consuming fried foods from outside the home, reflecting the availability at low prices and the appeal of such food items in the daily lives of university students and their families.

Figure 7.0 explains the places where fried food items are other than homemade. Among the sources of outside prepared fried foods, restaurants were the popular cited (71.9%), followed closely by university canteens (63.1%), which are dominant in student life and frequently provide appropriate, low-cost meals. Street vendors were also a significant source, mentioned by 29.9% of respondents. A few participants (14.5%) obtained fried food from other locations, such as food delivery services, tuck shops, or events.

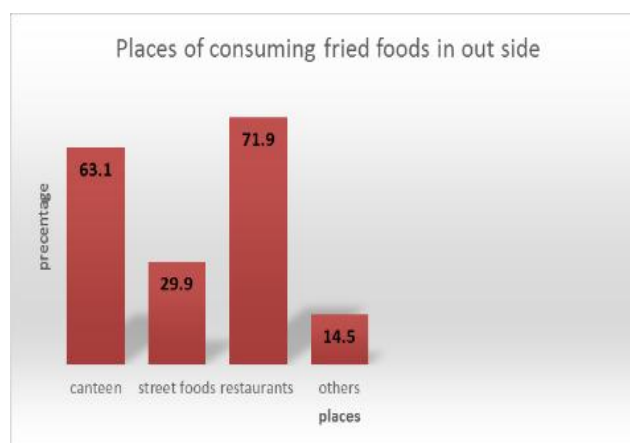


Figure 7: Places of consuming fried foods in outside

The analysis results of consumption frequency revealed that 49.9% of contributors consumed externally fried foods once per week, whereas 22.9% reported consumption twice weekly. 14.8% consumed this food more than twice per week, demonstrating a small but important group with possibly high contact with dietary fats and reused oils. Only a smaller percentage of participants (8.8%) did not answer this question, possibly representing non-eating or doubt about consumption patterns, predominantly in cases where meals are bought from outside or shared within families.

The high consumption of externally fried foods, especially from institutional sources such as university canteens, suggests high accessibility and addition of fried foods into weekly diets. Nevertheless, the relatively moderate rate of consumption (mostly once or twice weekly) may highlight rising awareness of the health risks associated with such behaviors, mostly the reuse of cooking oil in commercial kitchens, a practice known to produce toxic compounds such as aldehydes, trans fats, and oxidized triglycerides.

These outcomes of our study show the importance of food safety standards in food service organizations, especially those facilitating students and the young generation. Furthermore, public health education operations could focus on inspiring more informed choices, encouraging lower-fat alternatives, and promoting institutional policies that limit the reuse of oils and improve cooking methods in canteens and restaurants.

Figure 8.0 explains the awareness of trans fats among participants. The study also assessed participants' awareness of trans fats, a harmful class of dietary fats associated with increased risk of cardiovascular diseases, insulin resistance, and inflammation. Overall, 70.6% of participants reported being aware of trans fats, indicating a relatively high level of general knowledge regarding the presence and health risks of these compounds. However, 21.6% of respondents stated that they were not aware, and 7.8% were unsure, suggesting that around one-third of the population lacks a full understanding of this critical issue.

Despite this comparatively high awareness, the technical understanding of how to decrease or avoid trans-fat formation in cooking oils was very limited. A striking 97.1% of participants reported not knowing any methods to remove or minimize trans fats from used oil. Only 2.9% demonstrated some level of understanding, with answers indicating traditional practices such as adding rice or corn flour to absorb impurities and next discarding the oil. While these practices may decrease visible contaminants, they are not scientifically validated methods for effectively eliminating trans fats or lipid oxidation products. This significant disparity between general awareness and practical knowledge highlights a crucial gap in public understanding. Many participants are aware of trans fats and their associated health risks, but lack the technical knowledge required to mitigate these risks during daily cooking practices. This gap is particularly concerning given the high prevalence of frying and oil reuse observed among the study population.

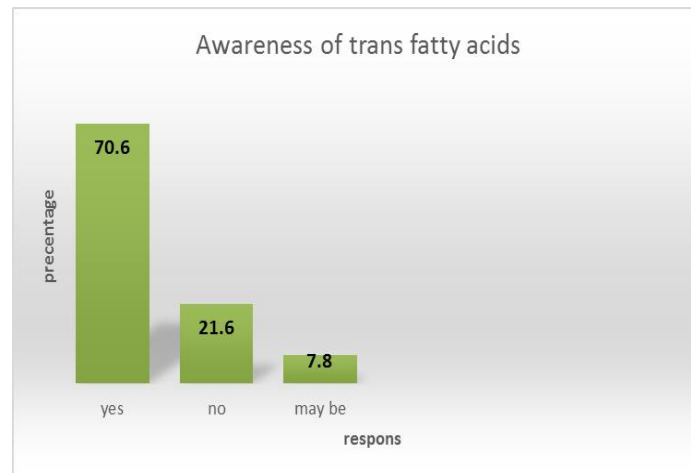


Figure 8: Awareness of trans fatty acids

These findings emphasize the need for targeted nutrition education campaigns that go beyond general awareness. Future interventions should aim to disseminate evidence-based information about trans-fat formation, such as the dangers of overheating oil, the risks of oil reuse, and the importance of selecting oils with a favorable fatty acid profile and high smoke point. In addition, public health messaging should clarify scientifically common practices, such as the belief that adding rice or flour can eliminate harmful substances, and instead promote safer, scientifically supported cooking practices.

A large majority (92.7%) were aware of the health hazards of excessive oil consumption, including its link to high cholesterol, cardiovascular disease, fatty liver, colon cancer, obesity, hypertension, stroke, and dyslipidemia. This high level of awareness is encouraging and aligns with findings from Özbek (2020), where 75% of participants believed oil intake contributes to cardiovascular disease.

The understanding of fatty acid profiles was moderate; 59.5% had knowledge, while 21% did not, and 19.5% were uncertain. In identifying the healthiest oil, 55.1% selected olive oil, 33.8% selected coconut oil, 6% selected sunflower oil, and 6.5% chose others. These findings are consistent with Özbek (2020), where olive oil was also rated as the healthiest.

The average per-person daily oil consumption was found to be 16.95 mL, approximately equivalent to one tablespoon. Given that one tablespoon of oil provides about 120 kcal, and assuming a daily energy requirement of 2000 kcal, this accounts for approximately 6% of daily energy intake. According to WHO and FAO guidelines, total fat intake should be less than 30% of total energy, and saturated fats should not exceed 10% (WHO, 2021; FAO, 2010). Although the observed intake appears within acceptable limits, it is essential to consider hidden fat intake from other dietary sources, such as meats, dairy, snacks, and commercial fried foods.

Moreover, the quality of fat consumed is just as important as quantity. An omega-6 to omega-3 fatty acid ratio of 5–10:1. Coconut oil, which dominates in this population, contains over 90% saturated fat, far exceeding healthy recommendations. In contrast, oils such as sunflower, soybean, and olive oil provide more favorable fatty acid profiles. These findings indicate a misalignment between popular oil choices and nutritional guidelines, particularly regarding cardiovascular health.

4. Conclusion

This study assessed the knowledge, attitudes, and practices related to cooking oil usage among undergraduates and their families. Results demonstrate a moderate to high level of awareness regarding the health impacts of oil consumption, yet actual practices, such as the predominant use of saturated-fat-rich coconut oil and low filtering of reused oil, highlight areas for improvement. Although most participants consume fried foods outside the home, the frequency and unsafe reuse practices in commercial kitchens remain a concern.

Importantly, while oil intake by quantity seems to be within WHO guidelines, the quality of fats consumed with high saturated fat intake and limited knowledge about healthier alternatives raises concern for the future risk of non-communicable diseases. Therefore, public health strategies should focus on promoting oils with healthier fatty acid profiles, reducing oil reuse, and encouraging the use of safer cooking methods.

Educational campaigns targeting university students and families can be an effective way to disseminate nutritional information and encourage behavioral change. Additionally, policy-level interventions, such as regulating the sale of loose oils and mandating labeling standards, could help improve the overall quality and safety of cooking oils available in the market.

In summary, the study successfully met its objectives by evaluating the average daily oil intake and related behaviors, and it provides critical insights into current consumption patterns. These findings can serve as a foundation for future interventions aimed at promoting healthier dietary fat consumption in Sri Lanka and similar contexts.

Acknowledgements

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**DEVELOPMENT OF READY TO SERVE (RTS) FLAVOURED COFFEE
BEVERAGES USING ROBUSTA COFFEE****Y. A. N. T. Jayasinghe¹, I. V. A. D. C. S. Induruwa^{2*}, C. A. K. Dissanayake¹, T. E.
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Abstract: Coffee is the second most consumed beverage in the world after water. However, flavor incorporated coffee beverages are retaining relatively uncommon in the global market. Therefore, this study aimed to develop ready-to-serve flavored coffee beverages using robusta coffee with ginger and cinnamon oleoresins. Hot, cold and brewing at room temperature methods were tested and the ideal method was selected by comparing their physicochemical and sensory properties. Among them, hot brewing method (75°C for 30 minutes) was selected as the optimal method due to its highest extraction yield (16.80±1.05%), physico-chemical (pH, Brix value) and sensory properties. Using the selected hot brewing method, pure robusta coffee (PRC), ginger flavored (GF) and cinnamon flavored (CF) coffee beverages were formulated with added citric acid, sodium bicarbonate and sugar. Optimal formulations were selected using sensory evaluations. The products were stored in refrigerator (4°C) following the pasteurization process. Accordingly, the selected PRC beverage contained 9.3% coffee and 7.4% sugar, whereas GF and CF beverages contained 9.26% and 9.34% coffee respectively, with 7.41% and 6.54% sugar, and 0.02% and 0.03% oleoresin respectively. Physico-chemical results revealed that GF beverage has the highest total polyphenol content (254.48±4.80 mgGAE 100g⁻¹), highest Brix value (12.29°) and highest preference in all sensory attributes. No significant differences were observed in caffeine contents (64.36±0.51-65.31±0.83 mg 180ml⁻¹), proximate compositions, pH and titratable acidity among the three beverages. Moreover, pH, Brix values and titratable acidity were not significantly changed during the 2 months of storage under refrigerated conditions. The beverages were free from yeast or mold counts and total plate counts were within the safe limits even after 2 months' storage. In conclusion, ready-to-serve beverages can be successfully formulated using hot brewing method and with locally sourced ginger and cinnamon flavors with a storage life more than 2 months in refrigerated conditions.

Keywords: Beverages; Brewing; Caffeine content; Cinnamon; Ginger; Robusta coffee

1. Introduction

Coffee is one of the most commonly consumed beverages in the world, accounting for 75% of the regular soft drinks consumption (Ciaramelli et al., 2019). Every day, approximately 2.25 billion cups of coffee are consumed globally (Cordoba et al., 2019). The two main commercial coffee species are *Coffea arabica* (Arabica coffee) and *Coffea canephora* (Conilon and Robusta varieties), where Arabica coffee, generally regarded as superior to robusta coffee in terms of sensory attributes, accounts for approximately 70% of world production. However, in certain regions, robusta coffee is used because of lower production costs and higher yield (Nebesny and Budryn, 2006). The popularity of coffee beverages arises from the stimulating effects of caffeine and from its pleasant aroma and flavor and, more recently, from its health benefits (Wang and Lim, 2021).

Though coffee is considered as one of the popular beverages worldwide, there is a lack of flavored coffee beverages in the market. But when consider about beverages such as tea, there are many flavor variations and product diversifications. Furthermore, in today's world there is a rising demand for the flavor incorporated coffee beverages. Among the flavors, ginger and cinnamon are one of the most commonly and widely used flavors in the beverage industry. In a country like Sri Lanka, these spices are readily available and are in higher quality. Moreover, when considering the regular coffee preparation methods, there are some challenges such as difficulty in achieving consistent coffee qualities like taste, aroma and processing factors like brewing time, water temperature, and coffee-to-water ratio (Mussatto et al., 2011). Furthermore, regular coffee brewing requires access to specific equipment making it less convenient in settings and process is time consuming. Freshly brewed coffee has a relatively short shelf life, especially when exposed to air and light.

Development of a ready-to-serve coffee beverage offers consumers a quick and hassle-free way to enjoy coffee without the need for further brewing or equipment. Ready To Serve (RTS) beverage is a packaged beverage which is sold in prepared form and it is ready for the consumption. Also, these properly packaged and preserved, ready-to-serve coffee beverages can have a longer shelf life compared to regular brewed coffee. This makes them suitable for stocking and distribution over a more extended period and has the ability to offer diverse coffee options. Hence, in the light of the above research facts, the present investigation was undertaken with the objective to develop a ready to serve flavored coffee beverage while optimizing the physicochemical and organoleptic properties of several brewing methods to select the ideal brewing method for the beverage preparation. Moreover, to study the physicochemical properties, storage and shelf life of the developed beverages at refrigerated temperatures.

2. Materials and Methods

2.1 Study location

The study was conducted at the postharvest division of the Export Agriculture Research Center, Department of Export Agriculture, Matale.

2.2 Materials

The main ingredient, coffee powder (Robusta) was purchased from a commercial scale coffee processing company located in Matale district. Other ingredients such as sugar, preservatives including citric acid (INS 330), Sodium hydrogen carbonate (INS 500 (II)) were purchased from local markets in Matale city area. Oleoresins obtained from local ginger (*Zingiber Officinale*) rhizomes and ceylon cinnamon (*Cinnamomum zeylanicum* Blume) barks were used as the flavors for the newly developed beverages and those oleoresins were extracted using soxhlet extraction process in the laboratory by using ethanol as the solvent.

2.3 Process of the development of Ready To Serve (RTS) flavored coffee beverage

2.3.1 Selection of the ideal brewing method for the new ready to serve flavored coffee beverage

Good quality, coarsely ground coffee beans were selected and the ratio of 1:7.5, coffee: water samples were prepared for the extraction (Angeloni et al., 2019). 25g of coffee and 187.5ml of distilled water were used and three brewing methods with several brewing conditions were tested as shown in the Table 1. Based on the available literatures and the preliminary trials, the ideal time and temperature

conditions for each of the three brewing methods were selected. Three replicates from each of the brewing methods were conducted.

Table 1: Brewing methods tested for the coffee extraction in beverage preparation

Treatment	Brewing method	Brewing conditions
TM 1	Cold brewing while stirring	5 ⁰ C for 6 hr
TM 2	Hot brewing while stirring	75 ⁰ C for 30 min
TM 3	Brewing at room temperature while stirring	28 ⁰ C for 1 hr

Source: (Angeloni et al., 2019)

Once the brewing is done with the above methods, the coffee extracts were filtered using a vacuum pump machine to get the coffee extract free from remaining coffee particles. The extracts were then analyzed for their extraction yield, pH, color values, brix values and sensory attributes to select the ideal brewing method for the new beverage preparation.

2.3.2 Determination of the physio-chemical and sensory properties of the coffee brews/extracts obtained from three brewing methods

Extraction yield

Filtered coffee extracts were concentrated and oven dried at 105⁰C for 1 hr period (Angeloni et al., 2019). Extraction yields were calculated by using Eq.(1). Three replicates from each of the brewing methods were tested.

$$EY = \frac{W_0}{W_I} \times 100\% \quad (1)$$

Where,

EY = Extraction Yield

W₀ = Oven dried weight of the sample

W_I = Initial weight of the coffee sample

Determination of the pH of the brewed coffee samples

An electronic digital pH meter (OHAUS, STARTER3100M) was used to measure the pH of the brewed samples. First, the filtered coffee extracts/brews were diluted for coffee: water in 1:10 ratio (Angeloni et al., 2019). Then 10 ml of the sample was taken and placed in a beaker. The pH was measured by immersing the electrode of the pH meter in the sample (Angeloni et al., 2019). Readings were taken in triplicate for each methods tested.

Determination of the color values of the brewed samples

The color values were determined by Chroma meter (KONICA MINOLTA color reader CR-10) and defined using L* a* b* values (Yeager et al., 2022). An immiscible volume of samples was poured into Petri dishes, and each sample was individually wrapped in cleaned polythene. The colorimeter sensor was placed on the polythene sheet so that it could touch the brewed coffee samples. Readings were taken in triplicate for each methods tested.

Determination of the Total Soluble Solids (TSS) / brix values of the brewed coffee samples

The Total Soluble Solids (TSS) value of the three brewed samples were recorded by using a hand refractometer (Erma, Japan) having range of 0-32 °Brix. Three readings were taken from each brewing methods and their average value was expressed in °Brix (Rashid et al., 2018).

Sensory evaluation for selecting the ideal brewing method

Sensory evaluation for the three brewing methods were carried for its color, taste, aroma, mouth feel, bitterness and overall acceptability by 30 untrained panelists using a 5-point hedonic scale, where 1 is “disliked very much” and 5 is “liked very much” as described by Cordoba et al., 2019.

2.3.3 Addition of flavors and development of the RTS coffee beverage formulations

Once the coffee brew was obtained, they were filtered well and diluted to 1:10, coffee: water (Angeloni et al., 2019). As the ingredients, sugar, citric acid (INS 330), Sodium hydrogen carbonate (INS 500

(II)) were used. Citric acid serves as an acidity regulator, antioxidant, color retention agent and as a sequestrant whereas Sodium hydrogen carbonate serves as an acidity regulator, stabilizer and as a thickener (Codex stan 192, 1995).

Three Ready To Serve (RTS) coffee beverages were prepared as pure robusta coffee RTS, cinnamon flavored coffee RTS and ginger flavored coffee RTS. For the flavors, oleoresins of the ginger and cinnamon were used. Those oleoresins were extracted from the solvent extraction method using ethanol as the solvent. Ginger and cinnamon were purchased from the local market and 10g of the powdered ginger/cinnamon samples were placed inside a thimble and inserted into the Soxhlet extractor. 200ml of ethanol was added to the unit and extractions were carried out for 6 hours. After the extraction is completed, ethanol was removed by evaporation, leaving only the oleoresins in the flask (Thomas and Kuruvilla, 2012).

For the beverage preparation, 100 ml of the coffee brews were taken those were brewed from the selected brewing method from the initial experiments. Three beverage formulations for each of the three beverages were prepared. For the pure robusta coffee RTS, three final beverage formulations were prepared by changing the sugar concentrations. These sugar levels were decided through preliminary trials while ensuring they remained within the safe limits recommended for beverages (Codex stan 192,1995). Similarly, for the ginger and cinnamon flavored RTS beverages, three final beverage formulations for each were developed by adjusting both sugar levels and oleoresin concentrations. There also, the adjustments were based on the preliminary trials to identify the acceptable flavor intensities and sweetness.

The best formulations were selected using a sensory test. Food additives were added as per the standard amounts recommended by the general standards for food additives (Codex stan 192,1995). Then the beverage mixtures were homogenized for about 1 min. Sterilized glass bottles were taken and the mix was filled into the glass bottles. Glass bottles were sealed well and then the bottles were pasteurized at 85°C for 20 min (Hariharan and Mahendran, 2016). Then the bottles were allowed to cool for ten minutes. Finally, the bottles were stored in refrigerator at 4°C (Hariharan and Mahendran, 2016). Table 2,3 and 4 displays the three treatment formulations developed for the pure robusta coffee RTS, Cinnamon flavored RTS and Ginger flavored RTS respectively.

Table 2: Beverage formulations prepared for the pure robusta coffee RTS beverage

Ingredients	Treatments		
	<i>PRC 1</i>	<i>PRC 2</i>	<i>PRC 3</i>
Sugar (%)	7	8	9
Citric acid (%)	0.0375	0.0375	0.0375
Sodium hydrogen carbonate (%)	0.0375	0.0375	0.0375

Each of the three formulations were made using 100ml of coffee brews prepared from the selected best brewing method.

Table 3: Beverage formulations tested for the cinnamon flavored coffee RTS beverage

Ingredients	Treatments		
	<i>CF 1</i>	<i>CF 2</i>	<i>CF 3</i>
Sugar (%)	7	8	9
Citric acid (%)	0.0375	0.0375	0.0375
Sodium hydrogen carbonate (%)	0.0375	0.0375	0.0375
Cinnamon oleoresin (%)	0.023	0.025	0.028

Each of the three formulations were made using 100ml of coffee brews prepared from the selected best brewing method

Table 4: Beverage formulations tested for the ginger flavored coffee RTS beverage

Ingredients	Treatments		
	<i>GF 1</i>	<i>GF 2</i>	<i>GF 3</i>
Sugar (%)	7	8	9
Citric acid (%)	0.0375	0.0375	0.0375
Sodium hydrogen carbonate (%)	0.0375	0.0375	0.0375
Ginger oleoresin (%)	0.023	0.025	0.028

Each of the three formulations were made using 100ml of coffee brews prepared from the selected best brewing method.

Sensory evaluation for selecting the best formulations for the three new beverages

Sensory evaluation for the beverage formulations of each of the three beverages were carried for its color, taste, aroma, mouth feel, bitterness and overall acceptability by 30 untrained panelists using a 5-point hedonic scale, where 1 is “disliked very much” and 5 is “liked very much” as described by Cordoba et al., 2019. The main aim of this sensory evaluation test was to select the most preferred beverage formulation for the new pure robusta coffee RTS, ginger flavored coffee RTS and cinnamon flavored coffee RTS.

2.4 Analysis of the physicochemical properties of the newly developed three RTS coffee beverages (Pure robusta coffee, Ginger and Cinnamon flavored coffee RTS)

2.4.1 Total Soluble Solids (TSS)

The Total Soluble Solids (TSS) value of the three RTS beverages were recorded by using a hand refractometer ((Erma, Japan) having range of 0-32 °Brix. Three replicates were taken from each beverage and their average value was expressed in °Brix (Rashid et al., 2018).

2.4.2 Determination of pH value

An electronic digital pH meter (OHAUS, STARTER3100M) was used to measure the beverage's pH. 10ml of beverage sample was taken and placed in a beaker. The pH was measured by immersing the electrode of a pH meter in the sample. Triplicate readings were taken from each of the beverage samples (Angeloni et al., 2019).

2.4.3 Total Titratable Acidity (TTA)

The acidity in each sample was determined according to standard procedure given in AOAC,2010. 10ml of the beverages along with 100ml distilled water was taken and then titrated with 0.1 N NaOH using phenolphthalein as an indicator (1-2 drops) till light pink color was achieved (Singh and Gaikwad, 2012). Triplicate readings were taken for each beverage samples.

2.4.4 Total Polyphenol Content (TPC)

Folin-Ciocalteu's method was used to determine the total polyphenol content of the developed beverages with minor modifications (Chang et al.,2002). 8ml from each of the beverages were taken into test tubes and each were dissolved in 100 ml of distilled water separately. Then another set of labelled test tubes were taken and each were added 3.16 ml of distilled water. Then 0.2 ml of Folin-ciocalteu reagent was added to each following 0.6 ml of Na₂CO₃. Then 40µL from previously diluted beverage sample solutions were added to relevant test tubes. Different micropipette tips were used for avoid contamination. Test tubes were vortexed and incubated for 2h hours in dark. Then absorbance was measured at 765nm using UV-vis spectrophotometer (Cary 60 UV-VIS, Agilent Technologies, California, USA). Blanks were created by substituting distilled water for the sample (Seneviratne et al., 2013). Three replicates from each of the beverage samples were conducted. Gallic acid was used as the standard for the calibration curve. The total phenolic content (TPC) was expressed as TPC mg GAE/ 100g.

2.4.5 Determination of the caffeine content

Determination of the caffeine contents in developed beverages were conducted using UV- visible spectrophotometer method. For that a series of working standard solutions of caffeine in the range of 0.016 mM to 0.102 mM concentration were prepared in distilled water. Using a UV-Vis spectrophotometer, the absorbance of four working standard solutions of pure caffeine in the range of 0.016 mM and 0.102 mM was measured at 273 nm (Gebeyehu, 2015). For the extraction of caffeine from coffee beverage samples, the procedure described by Belay was used (Belay et al., 2007). For that, the coffee sample solution was mixed with dichloromethane by volume ratio (25:25 mL). Triplicate readings were taken for each newly developed beverage.

2.4.6 Determination of the proximate compositions

The proximate analysis of moisture, ash, fat and protein of the developed beverage samples were determined using the standard methods of AOAC,2010 with three replicates for each of the analysis.

2.5 Sensory evaluation of the newly developed three beverages

A sensory evaluation was conducted for the newly developed three beverages (Pure robusta coffee RTS, Ginger flavored coffee RTS and Cinnamon flavored coffee RTS) for its color, taste, aroma, mouth feel, bitterness and overall acceptability by 30 untrained panelists using a 5-point hedonic scale, where 1 is “disliked very much” and 5 is “liked very much” as described by Cordoba et al., 2019. All the panelists were given cold servings at refrigerated conditions (2-8 °C).

2.6 Storage and shelf-life study for the newly developed beverages

The newly developed three beverages that stored in sterilized glass bottles followed by pasteurization were kept at refrigerated conditions (4°C) and changes of different physico-chemical parameters and microbiological counts were tested at 14 day intervals up to 2 months of storage period.

As the physico-chemical parameters, changes in the pH value, Total Soluble Solid (TSS) and Titratable Acidity (TA) were analyzed and for the microbiology study, total plate counts and yeast/mold counts were tested. Changes in the TSS, pH, and Titratable Acidity (TA) during the storage period was determined using the same standard protocols that were used for the previous experiments in the study and triplicate readings were taken for each of the developed beverages.

Microbiological studies

Prepared RTS were studied for microbial load over a two month of storage period in refrigerated conditions (4°C). Standard total plate count method was used to determine the bacterial growth by suspending 17.5g of Plate Count Agar (PCA) medium in 1 L of distilled water while yeast and mold count was determined using Potato Dextrose Agar (PDA). There, the media was prepared by suspending 39g of PDA in 1L of distilled water. The pour-plate technique was used to determine the colony counts in the study. A volume of 1ml of the beverage was added into 9 mL of sterilized distilled water and stirred well to prepare the 10^{-1} dilution. Then, a dilution series was prepared from 10^{-1} to 10^{-5} . Duplicate Petri dishes were used for each dilution for both bacteria and yeast/mold tests. 50 µL from each dilution was transferred into duplicate petri-dishes. The contents were properly mixed clockwise, anticlockwise, horizontally and vertically. Then, medias were allowed to solidify, and petri dishes were covered with parafilm. Under aerobic conditions, yeast and mold plates were incubated for 2-5 days at 32°C. Bacterial plates were aerobically incubated for 24 h at 37°C. All the colonies were counted using the colony counter ((ROCKER Galaxy 330, Taiwan) (Center for Food Safety and Applied Nutrition, 2001).

2.7 Statistical analysis

The experiments were produced in triplicate and evaluated under a completely randomized design (CRD). The collected data was subjected to analysis of variance (ANOVA). Significant difference between treatments was analyzed using the least square significance difference method (LSD) and was defined at $p \leq 0.05$. The statistical analysis was performed with IBM SPSS Version 22 software. Presence of any significant difference at 95% confidence interval, among the sensory parameters of the tested beverage formulations for new beverages, developed

three new beverages and brewing methods were analyzed by Friedman test using Minitab software.

3. Result and discussion

3.1 Selection of the ideal brewing method for the newly developing ready to serve flavored coffee beverages

3.1.1 Comparison of the physico-chemical parameters of the three brewing methods

pH values, extraction yield and brix values for the three brewing conditions; cold brewing, hot brewing and brewing at room temperature were evaluated to select the ideal brewing method as shown in Table 5. According to the results, highest extraction yield was recorded in the hot brewed sample and there was a significant difference ($p < 0.05$) in hot brewed sample compared to the cold brewed and sample brewed at room temperature. Furthermore, Wang and Lim (2021) have found that the ideal extraction yield is 18–22%. Thus, comparing the three brewed samples, hot brewed sample have shown the nearest ideal extraction yield.

According to the results of the pH values, pH of the hot brewed sample showed a significant difference ($p < 0.05$) compared to other two brewing methods. pH of the hot brewed sample was more acidic compared to other two methods as it has recorded the lowest pH value. pH of the brewed coffee usually ranges between 4.85–5.10 depending on its concentration (Rao and Fuller, 2018). Coffee is only slightly acidic. The compounds found in coffee, including trigonelline, kahweol, cafestol, caffeine, and chlorogenic acid, are what give it its acidity (Angeloni et al., 2019). Thus the ability of coffee acidity to enhance other flavors in a cup of coffee is considered as one of its primary advantages (Rao and Fuller, 2018).

When consider about the Brix values of the three brewed samples, highest ($p < 0.05$) brix value was identified in hot brewed sample. It is clear that, with the high temperature/heat, more compounds in the coffee grounds are extracted to the water during the brewing process. According to the literature, it has mentioned that, the brewing technique known as "hot extraction" has an impact on various aspects of the process, including the volatile compound profile, total solids content, caffeine content, and antioxidant activity (Corboda et al., 2019).

Table 5: Comparison of the three brewing methods for their extraction yield, pH value and brix value

Parameter	Cold brewed sample	Hot brewed sample	Sample brewed at room temperature
Extraction yield	12.70 ± 0.75^b	16.80 ± 1.05^a	13.88 ± 0.83^b
pH value	6.55 ± 0.09^a	5.95 ± 0.11^b	6.43 ± 0.06^a
Brix value	2.9 ± 0.05^b	3.4 ± 0.05^a	3.0 ± 0.05^b

The data are presented as mean $\pm$ standard deviation. Values with different superscripts in the same row are significantly different ($P < 0.05$)

When consider about the results of the color values of the brewed samples obtained from three brewing methods which displays in the Table 6, there was a significant difference in ($p < 0.05$) L^* and a^* values of the three samples brewed by different brewing methods. According to the results, hot brewed sample has recorded the lowest ($P < 0.05$) L^* value compared to other two brewed samples. Also hot brewed sample had the highest a^* and b^* value compared to other two brewed samples. In general, the hot brewed sample was more brownish color and cold brewed sample was more reddish color compared to other brewing methods tested. By comparing all the results of the three brewing methods, hot brewing method was selected as the best brewing method and it was used as the suitable method for the development of the new beverage.

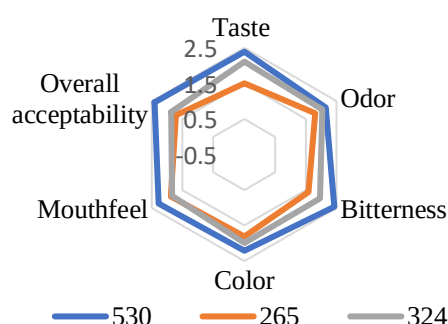
Table 6: Color values of the brewed coffee samples from three methods

Color values	Cold brewed sample	Hot brewed sample	Sample brewed at room temperature
L*	27.1±2.06 ^a	20.1±0.10 ^b	24.5±1.70 ^a
a*	13.1±0.93 ^b	17.6±0.77 ^a	17.5±2.06 ^a
b*	40.1±2.93 ^a	40.5±6.05 ^a	39.8±4.97 ^a

The data are presented as mean ± standard deviation. Values with different superscripts in the same row are significantly different (P < 0.05)

3.1.2 Sensory analysis for selecting the ideal brewing method

Results of the sensory analysis for selecting the ideal brewing method displays in the Figure 1. According to the results, hot brewed coffee sample (530) had the highest ($p < 0.05$) preferences for taste, color, odor, bitterness, mouthfeel and overall acceptability. However, cold brewed sample had the lowest preference in all of the sensory attributes. Furthermore, there was no any significant difference in mouthfeel, color and overall acceptability among cold brewed sample and sample brewed at room temperature. However, reason for the overall low sensory scores could be the natural strong and bitter notes of the robusta coffee used for the brewing process.



530 – Hot brewed sample, 265 – Cold brewed sample, 324 – Sample brewed at room temperature

Figure 4: Results of the sensory evaluation for selecting the best brewing method

By comparing the physico-chemical parameters and the results of the sensory analysis, hot brewed coffee sample was selected as the best brewing method. Furthermore, the new beverage developments were carried out with the use of hot brewing method.

3.2 Selection of the best formulations for the three newly developed RTS beverages

3.2.1 Selection of the best formulation for the pure robusta coffee RTS beverage

Table 7 displays the different formulations that were developed to select the best formulation for the new pure robusta coffee RTS beverage. Three sugar levels were tested in those three formulations that were decided based on the preliminary trials. According to the sensory results as mentioned in the Figure 2, the formulation with sugar 7.4% (PRC 2) was selected as the ideal formulation for the pure robusta coffee RTS beverage. PRC 2 formulation have shown the highest ($p < 0.05$) preference for taste, bitterness, mouthfeel and overall acceptability compared to other two formulations. No any significant difference was observed among the PRC 1 and PRC 3 formulations for the tested sensory attributes.

Table 7: Developed formulations for the pure robusta coffee RTS beverage.

Pure robusta coffee RTS	Sugar (%)	Coffee (%)	Water (%)
PRC 1	6.5	9.3	84.2
PRC 2	7.4	9.3	83.3
PRC 3	8.3	9.2	82.5

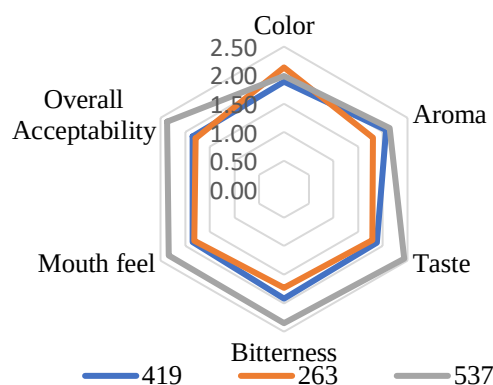


Figure 2: Results of the sensory evaluation for selecting the best formulation for pure robusta coffee RTS beverage

3.2.2 Selection of the best formulation for the ginger flavored coffee RTS beverage

Table 8 displays the different formulations that were developed to select the best formulation for the new ginger flavored coffee RTS beverage. Final three formulations were developed by changing the sugar and flavor amounts. According to the sensory results as shown in the Figure 3, the formulation with sugar 7.41% and flavor with 0.02% was selected as the ideal formulation for the new ginger flavored coffee RTS beverage. GF 2 formulation has recorded the highest preference for all the sensory attributes such as color, aroma, taste, mouth feel, mouth feel and overall acceptability. However, GF 1 formulation has recorded the lowest preference for color, bitterness, taste, aroma and overall acceptability from the other two formulations.

Table 8: Developed formulations for the ginger flavored coffee RTS beverage.

Ginger flavored RTS	Sugar (%)	Coffee (%)	Water (%)	Flavor (%)
GF 1	6.54	9.34	84.09	0.03
GF 2	7.41	9.26	83.31	0.02
GF 3	8.25	9.17	82.54	0.04

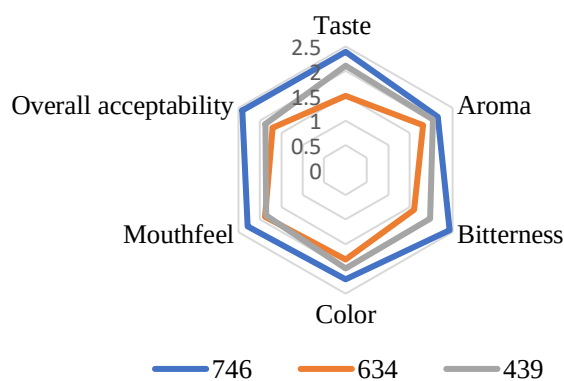


Figure 3: Results of the sensory evaluation for selecting the best formulation for ginger flavored coffee RTS beverage

3.2.3 Selection of the best formulation for the cinnamon flavored coffee RTS beverage

Table 9 displays the different formulations that were developed to select the best formulation for the new cinnamon flavored coffee RTS beverage. Final three formulations were developed by changing the sugar and flavor amounts. According to the sensory results as shown in the Figure 4, the formulation with sugar 6.54% and flavor with 0.03% was selected as the ideal formulation for the new cinnamon flavored coffee RTS beverage. CF 1 formulation has shown the highest preference for aroma, taste,

bitterness, mouthfeel and overall acceptability. However, no significant difference was identified in CF 2 and CF 3 formulations for their tested sensory attributes.

Table 9: Developed formulations for the cinnamon flavored coffee RTS beverage

Cinnamon flavored RTS	Sugar (%)	Coffee (%)	Water (%)	Flavor(%)
CF 1	6.54	9.34	84.09	0.03
CF 2	7.41	9.26	83.31	0.02
CF 3	8.25	9.17	82.54	0.04

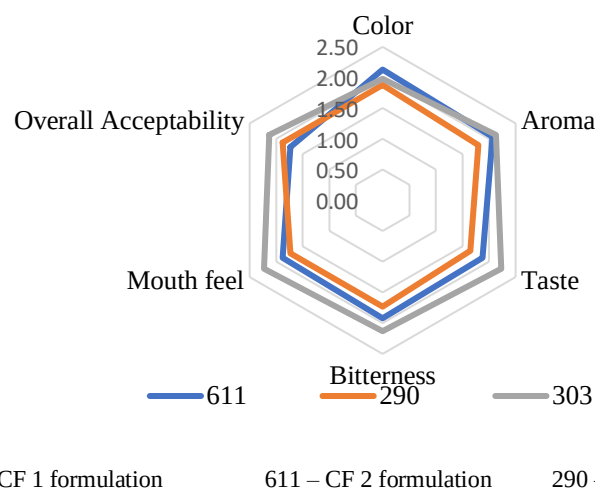


Figure 4: Results of the sensory evaluation for selecting the best formulation for cinnamon flavored coffee RTS beverage.

However, overall low sensory scores were recorded in selecting the ideal formulations for the developing beverages and the reasons could be the inherent strong and bitter notes of the robusta coffee and the interactions of the natural compounds in the ginger and cinnamon with components in the robusta coffee that influenced to the flavor and aroma perceptions of the selected panelists.

3.3 Analysis of physico-chemical parameters of the newly developed three beverages

3.3.1 Proximate compositions of the newly developed three beverages

The proximate compositions of the developed three beverages that are displays in Table 10 revealed that the beverages are free from fat. However, all the beverages contained protein and ash in very minute amounts. But the difference is not significant in any of the developed three beverages.

Table 10: Proximate compositions of the three beverages

Parameter	Pure robusta coffee RTS	Ginger flavored coffee RTS	Cinnamon flavored coffee RTS
Moisture (%)	89.03±0.01 ^a	89.22±0.43 ^a	89.03±0.03 ^a
Ash (%)	0.96±0.02 ^a	0.95±0.01 ^a	0.97±0.00 ^a
Fat (%)	0	0	0
Protein (%)	0.22±0.01 ^a	0.23±0.01 ^a	0.24±0.01 ^a

The data are presented as mean ± standard deviation. Values with different superscripts in the same row are significantly different (P < 0.05)

3.3.2 Total Polyphenol Contents (TPC) of the newly developed three beverages

According to the results of the TPC in three developed RTS beverages as shown in the Table 11, TPC content in ginger flavored RTS (254.48±4.80mg GAE/100g) was significantly higher (p<0.05) than the other two beverages. Besides the presence of polyphenols such as Trigonellin, Diterpenes, Caffeine, and Chlorogenic acid in coffee, ginger and cinnamon oleoresins are also rich in polyphenols (Yesil

and Yilmaz, 2013). This can be assumed for the increase of total polyphenol content in the ginger and cinnamon RTS beverages (Skaria et al., 2012 ; Thomas and Kuruvilla, 2012).

Table 11: Total Polyphenol Contents (TPC) of the three beverages

Parameter	Pure robusta coffee RTS	Ginger flavored RTS	Cinnamon flavored RTS
Total Polyphenol content (mgGAE/100g)	240.06±0.88 ^b	254.48±4.80 ^a	242.55±1.13 ^b

The data are presented as mean ± standard deviation. Values with different superscripts in the same row are significantly different (P < 0.05)

3.3.3 Caffeine contents of the newly developed three new beverages

According to the results of the caffeine contents of the newly developed three RTS beverages (Table 12), there was no any significant difference was observed in the caffeine contents among the three newly developed RTS beverages.

Table 12: Caffeine contents of the three beverages

Parameter	Pure robusta coffee RTS	Ginger flavored coffee RTS	Cinnamon flavored coffee RTS
Caffeine content in 180ml of beverage	65.31±0.83 ^a	64.36±0.51 ^a	64.73±0.70 ^a

The data are presented as mean ± standard deviation. Values with different superscripts in the same row are significantly different (P < 0.05)

3.3.4 pH, Total Soluble Solid (TSS) and Titratable Acidity (TA) of the newly developed three beverages

Results of the pH, TSS and TA of the developed beverages are displayed in the Table 13. According to the results, there was no any significant difference among the three new beverages for the caffeine contents.

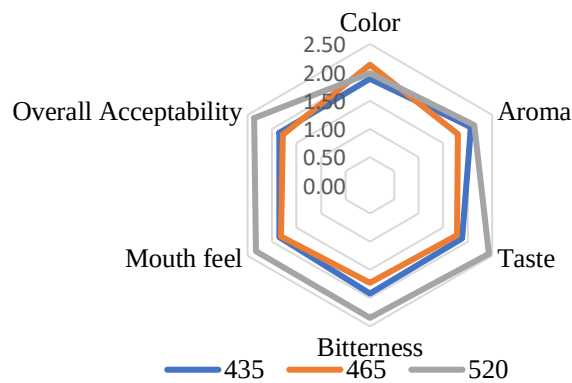
Table 13: pH, Total Soluble Solid (TSS) and Titratable Acidity (TA) of the three beverages

Parameter	Pure robusta coffee RTS	Ginger flavored coffee RTS	Cinnamon flavored coffee RTS
Total Soluble Solid (° Brix)	12.27±0.01 ^b	12.28±0.00 ^a	12.26±0.00 ^b
pH value	6.09±0.01 ^a	6.10±0.01 ^a	6.11±0.01 ^a
Titratable Acidity (TA) (%)	0.89±0.00 ^a	0.88 ±0.00 ^a	0.87±0.00 ^a

The data are presented as mean ± standard deviation. Values with different superscripts in the same row are significantly different (P < 0.05)

3.4 Sensory analysis for three flavored RTS beverages

The results of the sensory test which was carried out to identify the consumer preferences for different sensory attributes for the newly developed three flavored RTS beverages are displayed in the Figure 5. According to the results, ginger flavored RTS (520) had the highest preferences for taste, mouthfeel, bitterness and overall acceptability compared to other two beverages. The cinnamon flavored coffee RTS (465) and pure robusta coffee RTS (435) beverages did not show significant difference for the considered sensory attributes. However, cinnamon flavored coffee RTS (465) had shown the highest preference for color. Reasons for the low sensory scores could be the inherent strong and bitter notes of the robusta coffee and the interactions between different bioactive compounds in coffee and the added spices that influenced to the aroma and flavor perceptions of the selected panelists.



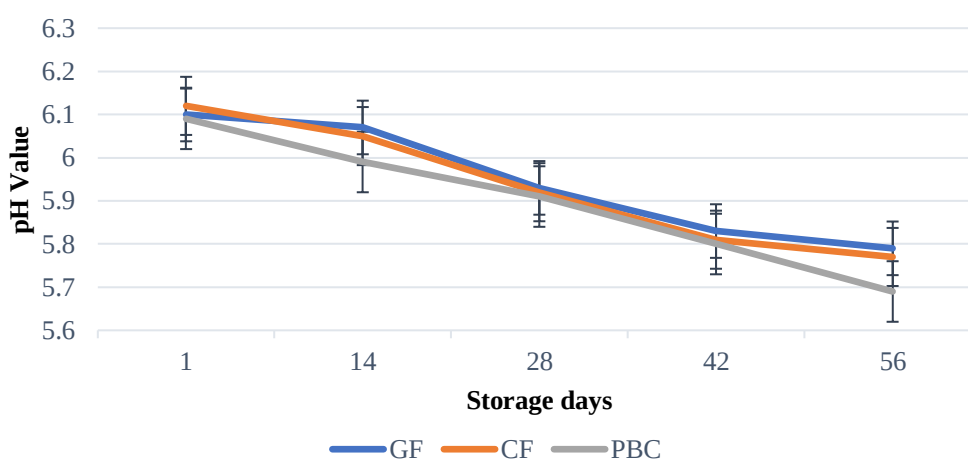
435 – Pure robusta coffee RTS 465 – Cinnamon flavored coffee RTS 520 –Ginger flavored coffee RTS
Figure 5: Results of the sensory evaluation of the newly developed beverages

3.5 Storage and shelf life study of the newly developed beverages

3.5.1 Changes in the pH value during storage

There was a decrease in the pH value during the storage of 2-month period as illustrates in the Figure 6. Furthermore, there was no significant difference in the pH value among the three newly developed beverages during the considered storage period. Since acidity and pH are inversely correlated, the cause of the pH drop could be an increase in titratable acidity (Mane et al.,2019). A higher degree of product acidity is indicated by a lower pH. The production of acid in coffee beverage products by microbiological activity, availability and degradation of acidic compounds in coffee itself and addition of citric acid as a food additive may causes the pH to decrease.

If consider about the drop of pH during 2-month of refrigerated storage, one reason could be the acid compound formation. Because, coffee's pH can vary due to the presence of several acidic substances, including chlorogenic acids. The beverage's pH may drop as a result of these components' potential to react or degrade over time and generate more acidic byproducts. Another reason could be the activity of microorganisms. Even though refrigeration slows down microbial growth, it doesn't completely halt it. Some microorganisms may still be present in the beverage. So the beverage's pH may be further lowered by the production of acidic chemicals as byproducts of microbial activity too. Apart from that, degradation of the organic acids such as citric, malic and acetic acids present in coffee also lead to the reduction of pH in the beverages (Mane et al.,2019).



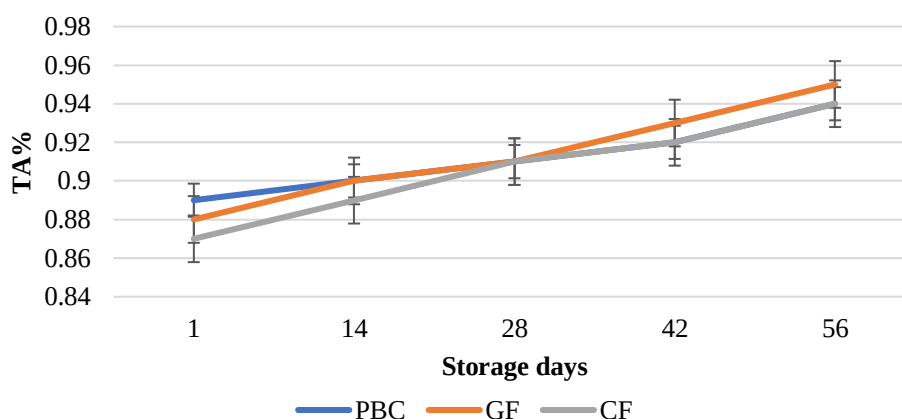
GF – Ginger flavored beverage CF – Cinnamon flavored beverage PBC – Pure robusta coffee beverage

Figure 6: Changes in the pH value during storage

3.5.2 Changes in the TA during storage

The results of the changes in TA over 2-month storage period is displayed in the Figure 7. According to the results, TA of the three developed RTS beverages were increased during the two month refrigerated storage. But the change was not significantly different. Reasons for increasing the acidity of the beverages could be the chemical changes that occur in the coffee such as chlorogenic acids, degradation of the organic acids and microbial activity even in the refrigerated storage conditions.

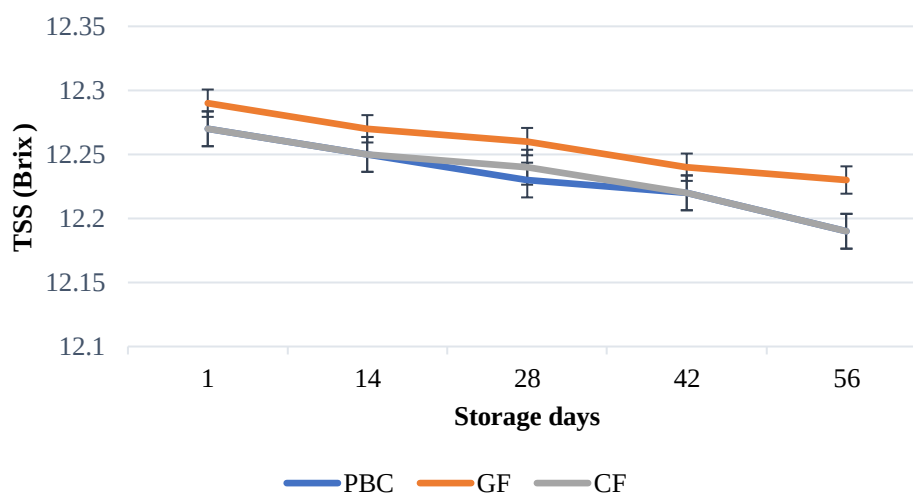
The titratable acidity determines a solution's ionic power, which controls the rate of chemical reactions (Hariharan and Mahendran, 2016). A product's ability to withstand microbial attack and maintain a shelf life is determined by its titratable acidity. The Sri Lanka Standard Institute Specifications state that the acceptable range of acidity for RTS preparation is between 0.3 and 1% in anhydrous citric acid (Hariharan and Mahendran, 2016).



GF – Ginger flavored beverage CF – Cinnamon flavored beverage PBC – Pure robusta coffee beverage
Figure 7: Changes in the TA during storage

3.5.3 Changes of TSS ($^{\circ}$ Brix) during storage

Changes of the TSS during the storage of the three beverages are shown in the Figure 8. The brix value of the three beverages were decreased with the storage. However, there was no significant difference in the TSS among the three beverages with storage. The breakdown of disaccharides into monosaccharides during the hydrolysis of sugars by acids, as well as the hydrolysis of sucrose, can all contribute to the decrease in total sugar. Polysaccharides that are soluble in reducing sugars can also leads to this (Cempaka et al., 2019).



GF – Ginger flavored beverage CF – Cinnamon flavored beverage PBC – Pure robusta coffee beverage
Figure 8: Changes in the TSS ($^{\circ}$ Brix) during storage

3.6 Microbiology study

The development and activity of microorganisms that break down food can affect both the quantity and quality of food. During storage, an increase in TDS parameters and a decrease in pH and total sugar (⁰Brix) parameters indicate that there is microorganism activity in the beverages (Cempaka et al., 2019). A total plate count of no more than 50 cfu/ml and a yeast and mold count of no more than 2 cfu/ml of sample are the microbial standards for carbonated drinks and ready-to-serve beverages (Mane et al., 2019).

According to the results of the microbiological study, a small increase in total plate count was observed in three beverages from the 42nd day of storage. But there was no any significant difference between the three beverages on the bacterial growth. However, the Total Plate Count was within the safe limits in ready to serve beverage (Mane et al., 2019). During entire storage period at the refrigerated conditions, there were no any evidence of yeast and mold in three prepared RTS beverages and hence it can be stored without any detrimental changes up to 60 days.

It can be assumed that the presence of ginger and cinnamon oleoresins which were extracted from ginger and cinnamon spices are strong antimicrobials, would provide resistance against microbial activity in the two flavored beverages (Hirdyani, 2016). Also, low microbial growths may be due to no microbial level of initial samples, weakening of bacterial growth by lower pH due to added Citric acid, bacterial death due to high temperature used in processing (Pasteurization at 85⁰ for 20 min), and effect of different acid contents present in the coffee could be the reasons for this low growth of microorganisms in prepared RTS (State, 2012).

As the prepared coffee RTS beverage bottles were pasteurized after filling, it increases the shelf life of prepared beverages by reducing the microbial load during storage. Addition of citric acid acts as a preservative by increasing the acidity of prepared RTS beverage that produces unfavorable conditions for the growth of microbes. Also, the low temperature during storage produced unsuitable conditions for growth of microbes in prepared products (Mane et al., 2019).

4. Conclusion

The present study concluded that, the hot brewing is the ideal brewing method for the new beverage preparation as it has recorded the highest extraction yield, sensory preference and physico-chemical parameters such as ideal pH, highest brix value and suitable color values. When selecting the best formulations for the beverages, formulation with sugar 7.4%, formulation with sugar 7.41% and 0.02% flavor and formulation with sugar 6.54 % and flavor 0.03% was found to be optimum for pure robusta coffee RTS, ginger flavored coffee RTS and cinnamon flavored coffee RTS respectively. On the basis of above results revealed in the present study it may be concluded that, cinnamon and ginger flavor incorporated coffee and pure robusta coffee can be successfully developed in to ready-to-serve (RTS) beverages. Furthermore, all these newly developed three beverages can be stored in refrigerated conditions for more than two months of storage period successfully.

Acknowledgement

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ICSD 140

**ENHANCING CONSUMER PREFERENCE OF ROBUSTA INSTANT COFFEE BY
INCORPORATING MICROENCAPSULATED CINNAMON; DEVELOPMENT AND
PHYSICOCHEMICAL ASSESSMENT OF A FLAVORED INSTANT COFFEE****Y. G. A. D. K. Bandara¹, I. V. A. D. C. S. Induruwa^{2*}, B. A. Perera¹, H. R. P. Fernando³, T. E. Weerawardena⁴**¹Department of Chemistry, University of Sri Jayewardenepura, Gangodawila, Nugegoda, Sri Lanka.²Division of Postharvest Technology, Central Research Station, Department of Export Agriculture, Matale, Sri Lanka³Food Research Unit, Department of Agriculture, Peradeniya, Sri Lanka⁴Division of Soil Science, Central Research Station, Department of Export Agriculture, Matale, Sri Lanka

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Abstract: This study was carried out to enhance the value of Robusta Coffee (*Coffea canephora*) which is around 80% of Sri Lankan coffee production, by developing an instant coffee and incorporating microencapsulated cinnamon extract powder to enhance its flavor and functional properties. The coffee and cinnamon used in the experiment were characterized. To maximize the yield of water-soluble solids in the extractions, various coffee-to-water and cinnamon-to-water ratios were tested using the maceration technique. The coffee extract was spray-dried to produce instant coffee powder, while the cinnamon extract was microencapsulated using maltodextrin as the carrier material through spray drying. Two distinct instant coffee formulations containing microencapsulated cinnamon powder, namely F₁(50% instant coffee, 50% cinnamon) and F₂(60% of instant coffee, 40% cinnamon) were developed and sensory evaluation was conducted to determine consumer acceptance. In addition, the color, moisture, solubility, wettability, water activity, encapsulation efficiency, bulk density, total flavonoid content, total polyphenol content, and antioxidant activity of both the instant coffee and cinnamon powders were determined. Pure instant coffee had a total phenolic content (TPC) of 57.7 ± 0.06 mg gallic acid equivalent (GAE)/g, a total flavonoid content (TFC) of 63.6 ± 0.1 mg quercetin equivalent (QE)/g, and an IC₅₀ value of 16.4 ± 0.8 mg L⁻¹ for DPPH radical scavenging activity. F₂ demonstrated higher sensory qualities, with appreciable values for TPC (46.8 ± 0.5 mg GAE/g), TFC (62.5 ± 0.1 mg QE/g), and antioxidant activity (IC₅₀ of 31.9 ± 0.2 mg L⁻¹). Conversely, F₁ demonstrated a TPC of 35.0 ± 0.06 mg GAE/g, TFC of 59.0 ± 0.04 mg QE/g, and antioxidant activity (IC₅₀ of 29.8 ± 0.3 mg L⁻¹). The study concluded that the inclusion of microencapsulated cinnamon significantly improved the sensory attributes and consumer acceptability of the instant coffee, thereby presenting a promising strategy to enhance the market value of Sri Lanka's coffee industry.

Keywords: Robusta coffee; Microencapsulation; Functional beverages; Flavour enhancement; Spray drying; Antioxidant properties

1. Introduction

Coffee is a widely consumed beverage and the world's second most highly traded commodity next to crude oil (Baffes et al., 2005). The coffee industry is a significant generator of global trade, uniting economic relations between the developed and developing countries, and is worth billions of dollars globally. During the 19th century, Sri Lanka, which is also known as Ceylon, was a key figure in the global coffee export market. Coffee cultivation peaked at 111,400 hectares (Ha) in 1870. The crop was, however, gradually devastated by a leaf rust disease. In the 1890s, the coffee plantations have shrunk, to a mere 4,609 hectares. This shift from agricultural activity came with a phenomenal increase in production of tea that became the predominant issue of the industry. In the 1970s, the industry returned to its peak, when the Department of Export Agriculture was established. The organization acknowledged the economic viability of the plant as a profitable crop and introduced support schemes with the objective of making available to farmers free seedlings, financial subsidies, and advisory services. Robusta seedlings were distributed to farmers under the first phase of the scheme to plant in their home gardens. Sri Lanka is now a net importer of coffee. The year 2017 recorded a huge disparity in imports and exports with the latter being almost five times larger than the former. The present domestic Arabica coffee production is not enough to facilitate the exportation of a lot of coffee, with the majority of the harvest being consumed in the local market. Global coffee consumption is not affected in any significant extent by Sri Lanka, owing to its relatively smaller size of output, higher price, and established reputation for cultivating great tea over coffee. Available data indicate that, more than eighty percent of current Sri Lankan production consists of Robusta (MDF, 2020), which traditionally falls under commodity coffee rather “Specialty coffee”.

In the coffee market, "Specialty coffee" is the term applied to coffee beans of superior quality that are cultivated in particular microclimates and subjected to strict processing methods to maintain their unique flavors and properties. The beans in question are generally cultivated at high altitudes and are subjected to selective picking and sorting procedures to guarantee consistency. Commodity coffee, which differs from specialty coffee, is a type of coffee that is produced on a large scale and typically found to be sourced from small-scale farmers. Sri Lanka's coffee crop predominantly consists of this Robusta (*Coffea canephora*) beans, which were neither properly processed nor selectively harvested (MDF, 2020). Bean blending from numerous sources is typical in the business with the aim of developing an even flavor experience. But this approach could lead to a lessened sensory experience due to the absence of detectable attributes. Commodity coffee, in contrast to specialty coffee, is usually roasted in mass volumes and sold to wholesalers and distributors at relatively lower prices.

The Sri Lankan coffee industry is currently facing different challenges. One of the ways through which such challenges can be overcome is by creating a new coffee product that adds value to the majority of commodity coffee production, which is otherwise synonymous with low value. This kind of strategy can potentially create a new market window for the majority of suppliers.

This study developed spray-dried microencapsulated cinnamon-enhanced instant coffee and evaluated its physicochemical properties. This research examined whether it is possible to convert this commodity coffee into instant coffee while minimally losing vital chemical components. Instant coffee was produced using a dark-roasted blend of Sri Lankan Robusta coffee (French style roast type by Kiyota Coffee Company Private Limited) via spray drying. Physicochemical parameters were evaluated, and flavor enhancement was achieved by adding microencapsulated cinnamon extract. Microencapsulated cinnamon improved the aroma, taste, polyphenols, and flavonoids in spray-dried instant coffee. The 2,2-Diphenyl-1-picrylhydrazyl (DPPH) assay, Aluminium Chloride Colorimetric (ACC) Assay, and Folin-Ciocalteu assay were used to assess antioxidants, flavonoids, and polyphenols in the product, respectively. The intended objective was to produce a product with additional value for the Sri Lankan coffee industry that maximizes production utilization.

2. Materials and Methods

2.1 Materials

2.1.1 Chemicals

The following chemicals were used in this research: Tricalcium phosphate (Jiangsu Kolod-China), maltodextrin (Roquette-India), folin-ciocalteu reagent (Alpha chemika-India), sodium carbonate (Techno Pharmchem-India), methanol (Fisher Scientific-UK), gallic acid (Fisher Scientific-UK), quercetin standard (Sisco Laboratories-India), potassium acetate (Himedia-India), aluminium Chloride (Duksaw-China), 2,2-diphenyl-1-picrylhydrazyl (DPPH) (Sigma-aldrich, Germany), ethanol absolute (VWR chemicals-India), Hexane (Merck-India)

2.1.2 Raw materials

Robusta (French style roast) coffee powder was supplied by Kiyota coffee company (Pvt) Ltd. Dried inner bark of Ceylon true cinnamon (*Cinnamomum verum*, C-1 grade) was locally purchased and powdered using a laboratory-scale blender (Philips HL7699/9).

2.2 Methods

2.2.1 Characterization of Raw Materials

Both Soxhlet and maceration extractions were employed in this study for different purposes. Soxhlet extraction was used to determine the maximum achievable percentage of water-soluble solids from Robusta coffee and cinnamon under ideal conditions, serving as a reference for extraction potential. In contrast, maceration was selected for actual product development due to its practicality, lower energy consumption, and alignment with food-grade processing standards. The results from Soxhlet extraction guided the optimization of maceration conditions, where different solid-to-solvent ratios were tested to identify the most effective and scalable extraction parameters for use in subsequent formulation steps.

Soxhlet Extraction

The water-soluble solid content of Robusta dark roasted coffee (French-style roast) and powdered cinnamon was determined using Soxhlet extraction with slight modifications based on the method described by Bravo *et al.* (2013). Coffee samples (7.00 g) and cinnamon samples (8.00 g) were accurately weighed and placed in cellulose extraction thimbles. Extraction was performed in triplicate using a Soxhlet apparatus equipped with a pre-weighed round-bottom flask, Soxhlet extractor, and condenser. Distilled water (200.0 mL) was used as the extraction solvent, and reflux was maintained for 5 hours until the solvent appeared clear.

After extraction, the solvent was removed by distillation, leaving behind the solid residue. The round-bottom flask was cooled in a desiccator and re-weighed to determine the mass of the extracted solids. The percentage of water-soluble solids was calculated using:

$$\text{Percentage of Water Soluble Solids} = \left(\frac{\text{Final flask weight} - \text{Initial flask weight}}{\text{Sample Weight}} \right) \times 100\% \quad (1)$$

Maceration Extraction

Maceration was performed at different coffee-to-water ratios (1:5, 1:7.5, 1:10, 1:12.5, and 1:15) and cinnamon-to-water ratios (1:5, 1:7.5, 1:10, 1:12.5, and 1:15) to determine the optimal extraction conditions.

For coffee, 20.00 g of sample was combined with varying volumes of distilled water corresponding to the tested ratios (1:5, 1:7.5, 1:10, 1:12.5, and 1:15) in a temperature-controlled magnetic stirrer (ARE VELP Scientifica). Each mixture was stirred at 85°C for 1 hour at a stirring speed of 5 (Stanek *et al.*, 2021). The setup was then cooled for 15 minutes, followed by vacuum filtration (8730 KNF Neuberger PTFE diaphragm vacuum pump) using Johnson No. 1 filter paper. The filtrate from each ratio was collected in a pre-weighed round-bottom flask, and the solvent was removed by distillation. The solid residue was dried and weighed to determine the water-soluble solid content for each extraction condition.

For cinnamon, 50.00 g of the sample was extracted with varying volumes of distilled water at ratios of 1:5, 1:7.5, 1:10, 1:12.5, and 1:15 under identical conditions, with extraction carried out at 70°C according to the method described by Khedkar and Ahmad Khan (2023). The extract from each ratio was centrifuged (BK-T4KZ Biobase) at 3,000 rpm for 3 minutes, followed by vacuum filtration. The filtrates were then processed similarly to the coffee extracts to determine water-soluble solid content.

Determination of Total Soluble Solids (TSS)

The total soluble solids (TSS) of macerated extracts were measured using a portable refractometer (Atago Co., Tokyo, Japan) at 25°C, and results were expressed in °Brix according to the methodology by (Bintoro, Miftahurrahim and Rizqiyati, 2023)

Color Measurement of Robusta Dark Roasted Coffee

The color of Robusta dark roasted coffee powder was analyzed using a Konica Minolta CR-10 tristimulus colorimeter (Ni'mah, Hasbullah and Retnowati, 2021). Coffee powder samples were placed on a flat surface to form a uniform layer. The colorimeter was positioned above the sample, and Lab color values* were recorded in triplicate.

Determination of Moisture Content

The moisture content of Robusta dark roasted coffee was determined using the oven-dry method (Lestari, Susanti and Legowo, 2018). Coffee samples (5.00 g each) were placed in moisture cans and dried in a preheated oven at 105°C until a constant weight was achieved. The moisture content was calculated using:

$$\text{Moisture content (\%)} = \left(\frac{\text{initial weight} - \text{final weight}}{\text{final weight}} \right) \times 100 \quad (2)$$

2.2.2 Product Development

Extraction of Robusta Dark Roasted Coffee

Robusta dark roasted coffee (French-style roast) was extracted according to the (Stanek et al., 2021) using the maceration technique at 85°C with a coffee-to-water ratio of 1:7.5. The extract was vacuum-filtered (8730 KNF Neuberger PTFE diaphragm vacuum pump) using Johnson No. 1 (110 mm, Grade 304) filter paper to remove solid particles. The filtrate was then concentrated by distillation, reducing the water content by 50%, and subsequently cooled and preserved at 0–5°C before spray drying.

Extraction of Cinnamon

Cinnamon extraction was performed by maceration at 70 °C using a cinnamon-to-water ratio of 1:10, following the method of Khedkar and Ahmad Khan (2023), with minor modifications. The extract was centrifuged (BK-T4KZ, Biobase) at 3,000 rpm for 3 minutes, then vacuum filtered using a PTFE diaphragm vacuum pump (8730, KNF Neuberger) and Johnson No. 1 filter paper to obtain a clear solution. The filtrate was subsequently concentrated to 2.5 times its original concentration by distillation, cooled, and stored at 0–5 °C for further processing.

The extraction temperature of 70 °C was selected based on prior literature demonstrating that moderate thermal conditions enhance the solubility and diffusion of phenolic compounds from plant matrices without causing significant thermal degradation (Khedkar and Ahmad Khan, 2023). Extractions at temperatures below 60 °C often yield lower concentrations of bioactives due to limited mass transfer, while temperatures above 80 °C risk degradation of heat-sensitive compounds such as cinnamaldehyde and polyphenols (Fang et al., 2011).

Preparation of Cinnamon-Maltodextrin Emulsion for Spray Drying

A total of 1,130 mL of concentrated cinnamon extract was prepared, to which 271.1 g of maltodextrin was added. The mixture was homogenized using a Micra D-8 high-performance homogenizer at approximately 16,000 rpm (corresponding to speed level 'B', as inferred from manufacturer specifications) for 5 minutes, with 30-second intervals between cycles to minimize foaming, following the method of Santiago-Adame *et al.* (2015) with slight modifications.

Determination of Emulsion Stability Index (ESI)

The emulsion stability index (ESI) was determined following a modified method from Chranioti et al. (2013). A 30 mL sample of the emulsion was transferred to a flat-bottom test tube and stored for 24 hours. The ESI was calculated using the formula:

$$ESI = \frac{\{HE - (HS + HC)\}}{HE} \times 100 \quad (3)$$

Preparation of Concentrated Coffee Extract for Spray Drying

A total of 3,060 mL of extracted coffee was mixed with 40 mg of tricalcium phosphate (Codex Alimentarius, 2021) as an anti-caking agent. The extract was then homogenized using a Micra D-8 high-performance homogenizer at approximately 24,000 rpm (corresponding to speed level 'D', based on manufacturer specifications) for 5 minutes to ensure uniform dispersion.

Spray drying was performed based on the procedure outlined by Anandharamakrishnan and Padma Ishwarya (2015), with modifications.

The homogenized coffee and cinnamon extracts were spray-dried separately on a laboratory-scale spray dryer (Ohkawara Kakohki L-8). Operating conditions were set to an inlet temperature of 148 °C, an outlet temperature of 70 °C, an atomizer frequency of 45 Hz, a cyclone-separator pressure drop of 80 mm H₂O, and an atomizer speed of 4,500 rpm. The resultant instant coffee powder and encapsulated cinnamon powder were collected in air-sealed aluminium flip-top bags, weighed, and stored for further analysis.



Figure 1. Spray dryer (Ohkawara kakohki L-8) at Food research unit, Department of Agriculture, Peradeniya

Preparation of Formulations

Two formulations were prepared by blending spray-dried instant coffee and encapsulated cinnamon powder in defined ratios. Formulation 1 (F₁) consisted of 50% instant coffee and 50% encapsulated cinnamon, while Formulation 2 (F₂) contained 60% instant coffee and 40% encapsulated cinnamon. The mixtures were homogenized to ensure uniform composition before further analysis.

2.1.3 Analysis of Physical Properties

Color Measurement

The color of instant coffee and encapsulated cinnamon powders was measured using a Konica Minolta CR-10 Tristimulus Colorimeter. A small portion of each sample was evenly spread on a clean, flat surface, and the instrument was aligned at the center of the sample for measurement. Color data were recorded as Lab values* based on the CIELAB color space. Measurements were performed in triplicate under consistent conditions.

Moisture Content

The moisture content of instant coffee and cinnamon powders was determined using the oven-dry method (A-Sun et al., 2016). A 1.00 g sample was placed in a pre-weighed moisture can and dried at

105°C in a preheated oven until a constant weight was achieved. The moisture content was calculated using:

$$\text{Moisture content (\%)} = \left(\frac{\text{initial weight} - \text{final weight}}{\text{final weight}} \right) \times 100 \quad (2)$$

Solubility Determination

The solubility of instant coffee and cinnamon powders was evaluated following a modified method from A-Sun et al. (2016). A 2.00 g sample was dispersed in 200.0 mL of distilled water at room temperature in a 250 mL glass beaker. The mixture was stirred using a magnetic stirrer (ARE VELP Scientifica, 4 cm magnet, speed level 5), and the time required for complete dissolution was recorded. The procedure was performed in triplicate for both samples.

Bulk Density

The bulk density of instant coffee and cinnamon powders was determined using a modified method from Goula and Adamopoulos (2008). A 25 mL graduated measuring cylinder was pre-weighed, and the powder was added until it occupied a volume of 4.00 cm³. The cylinder was tapped to settle the powder, and the final weight was recorded.

Encapsulation Efficiency of Cinnamon Powder

Encapsulation efficiency (EE%) was determined using a modified method from Chranioti et al. (2013). It represents the percentage of non-surface core material relative to the total core material in the encapsulated powder, calculated as:

$$\text{Encapsulation efficiency} = \frac{T_o - S_o}{T_o} \times 100\% \quad (4)$$

Where:

S_o = Mass of surface core material in microcapsules

T_o = Total mass of core material in encapsulated powder

A 2.00 g sample was vortexed with 25 mL of hexane for 2 minutes, then vacuum-filtered using Whatman No. 1 filter paper. The residue was washed with 15 mL of hexane, and the filtrate was transferred to a pre-weighed Petri dish. The solvent was evaporated in a fume hood at room temperature, and the remaining mass was weighed to determine the surface core material content. The total core material was calculated based on the core content in the initial emulsion.

Encapsulation Yield of Cinnamon Powder

Encapsulation yield (EY%) was calculated using:

$$\text{Encapsulation yield} = \frac{W_e}{W_t} \times 100\% \quad (5)$$

Where:

- W_e = Weight of encapsulated powder
- W_t = Total weight of wall material and core material

Wettability

The wettability of instant coffee and cinnamon powders was determined using a modified method from A-Sun et al. (2016). A 2.00 g sample was carefully placed on the surface of 80.0 mL of distilled water in a beaker from a height of approximately 6 cm. The time required for complete wetting of the powder was recorded. The procedure was performed in triplicate for both samples.

Determination of Water Activity

The water activity (A_w) of instant coffee and cinnamon powders was measured using a water activity meter (MRC WAM-1) at a controlled temperature of 29.2°C. A 2.00 g sample was placed in a plastic cup, and the measurement was recorded.



Figure 2. Water activity meter (mrc WAM-1) at Food research unit, Department of Agriculture, Peradeniya

Analysis of Chemical Properties

Total Polyphenol Content (TPC)

Total polyphenol content (TPC) was determined using the Folin-Ciocalteu method with minor modifications (Singleton and Rossi, 1965). Gallic acid standards (62.5–500 mg/L) were prepared for calibration. A 0.80 g sample of instant coffee, encapsulated cinnamon powder, and formulations (F₁ and F₂) was dissolved in 100 mL distilled water. A reaction mixture containing 0.2 mL Folin-Ciocalteu reagent, 0.6 mL of 7.5% Na₂CO₃, and 3.16 mL distilled water was incubated in the dark for 2 hours. Absorbance was measured at 765 nm using a UV-Vis spectrophotometer (Cary 60, Agilent Technologies, USA). Results were expressed as mg gallic acid equivalent per gram of sample (mg GAE/g).

Total Flavonoid Content (TFC)

Total flavonoid content (TFC) was determined using an aluminum chloride colorimetric assay (Indiarto et al., 2022). Quercetin standards (10–80 mg/L) were prepared for calibration. A 0.80 g sample of each test material was dissolved in 100 mL distilled water. A reaction mixture containing 1 mL sample, 3 mL methanol, 0.2 mL 10% AlCl₃, 0.2 mL 1M CH₃COOK, and 5.6 mL distilled water was incubated for 30 minutes in the dark. Absorbance was measured at 415 nm using a UV-Vis spectrophotometer. Results were expressed as mg quercetin equivalent per gram of sample (mg QE/g).

Antioxidant Activity (DPPH Radical Scavenging Assay)

Antioxidant activity was evaluated using the DPPH radical scavenging assay (Indiarto et al., 2022). A 2 mg/mL DPPH solution was prepared in absolute ethanol and stored in the dark. A 10 mg sample of each test material was dissolved in 100 mL distilled water, followed by serial dilution (0.1–0.00625 mg/mL). 4 mL of DPPH solution was mixed with 2 mL of each sample, vortexed, and incubated in the dark for 30 minutes. Absorbance was measured at 517 nm. The radical scavenging activity (RSA%) was calculated using:

$$\text{RSA\%} = \frac{\text{Absorbance of control} - \text{Absorbance of sample}}{\text{Absorbance of control}} \times 100 \quad (6)$$

2.1.4 Sensory Evaluation

A hedonic test was conducted to evaluate the sensory attributes of the two formulations (F₁: 50% coffee, 50% cinnamon; F₂: 60% coffee, 40% cinnamon) compared to a control sample (without cinnamon) (Indiarto et al., 2022). Thirty untrained panelists assessed color, texture, aroma, acidity, flavor, and overall acceptability using a 7-point hedonic scale (1 = Extremely Dislike, 7 = Extremely Like). Samples were coded and presented randomly, with palate cleansing between evaluations. Data were statistically analyzed to determine significant differences between formulations.

Statistical Analysis

All experimental measurements were conducted in triplicate (n=3), and the results are expressed as the mean ± standard deviation (SD). Statistical analysis of the chemical properties of developed instant coffee, encapsulated cinnamon powders, and formulated coffee blends was performed using one-way analysis of variance (ANOVA), followed by Tukey's post-hoc test, utilizing MINITAB statistical

software (version 20.3) at a significance level of 0.05. For sensory data analysis, the non-parametric Friedman rank sum test was applied to evaluate differences among the formulations, and the Mann-Whitney U test was used for pairwise comparisons, both performed using MINITAB software (version 19, Minitab Inc., State College, PA, USA).

3. Results and Discussion

Water-Soluble Solid Yield from Soxhlet Extraction

Soxhlet extraction yielded the highest theoretical water-soluble solid content: $32.15 \pm 0.34\%$ for dark-roasted Robusta coffee and $9.87 \pm 0.21\%$ for powdered cinnamon. These values served as benchmarks for evaluating maceration efficiency. The higher solubility of coffee is attributed to its abundance of hydrophilic compounds such as chlorogenic acids and caffeine (Bravo et al., 2013).

Optimization of Maceration Conditions

Maceration was tested at five solid-to-solvent ratios (1:5 to 1:15) for both materials. For coffee, the 1:7.5 ratio yielded the highest extraction ($27.83 \pm 0.38\%$), representing ~87% of the Soxhlet yield. Further dilution did not improve efficiency, likely due to solute saturation. For cinnamon, the 1:10 ratio yielded the highest solids ($7.71 \pm 0.27\%$), about 78% of the Soxhlet yield; higher dilutions slightly reduced efficiency.

Comparison of Extraction Methods

Soxhlet extraction gave superior yields due to continuous solvent cycling but is energy-intensive and less practical for food applications. Maceration offers lower yet sufficient yields, better suitability for thermolabile compounds, and is more scalable for food-grade processing.

Selected Extraction Conditions

Ratios of 1:7.5 for coffee and 1:10 for cinnamon were selected for further formulation, offering an optimal balance between yield, energy efficiency, and industrial applicability.



Figure 3. Appearances of the instant coffee (left) and encapsulated cinnamon (right) powders

Physical Properties

Table 01 presents the physical properties of instant coffee and encapsulated cinnamon powder, highlighting key differences influenced by the encapsulation process. Encapsulated cinnamon exhibited lower moisture content and water activity compared to instant coffee, suggesting improved stability and reduced susceptibility to microbial growth. However, its solubility and wettability were significantly lower, indicating a slower dissolution rate and reduced water absorption, likely due to the encapsulation matrix.

Encapsulation efficiency and yield for cinnamon powder were high (95.6% and 88.89%, respectively), confirming the effectiveness of the encapsulation process in retaining the material. Additionally, the higher bulk density of encapsulated cinnamon suggests improved packing properties, making it more compact compared to instant coffee.

These findings indicate that while encapsulation enhances the stability and handling properties of cinnamon powder, it also alters its solubility and wettability characteristics, which may influence its functionality in various applications.

Table 01. Results of physical properties of developed instant coffee and encapsulated cinnamon powders.

	Instant coffee	Encapsulated cinnamon
L* (Brightness)	32.0±1.36	55.3±0.100
a* (Red-Green)	13.5±0.866	13.5±0.208
b* (Blue-Yellow)	39.2±0.231	39.6±0.173
Moisture %	2.48±0.744	1.69±0.513
Solubility (Seconds)	68.0±3.00	116±5.03
Wettability (Seconds)	424±5.13	2550±147
Water activity	0.248±0.00907	0.144±0.00404
Encapsulation efficiency	-	95.6±0.211%
Encapsulation yield	-	88.89%
Bulk density (Kgm-3)	296±0.119	428±0.0660

Chemical Properties

Table 02 presents the total phenolic content (TPC), total flavonoid content (TFC), and antioxidant activity (IC₅₀) of instant coffee, encapsulated cinnamon, and two formulated blends (F₁: 50%-50%, F₂: 60%-40%), with statistical analysis using Tukey's test ($p < 0.05$) confirming significant differences among the samples. Instant coffee exhibited the highest TPC (57.7 ± 0.06 mg GAE/g) and TFC (63.6 ± 0.1 mg QE/g), while encapsulated cinnamon had the lowest values (11.9 ± 0.01 mg GAE/g and 11.7 ± 0.005 mg QE/g, respectively). The formulated blends demonstrated intermediate values, with F₂ containing significantly higher TPC and TFC than F₁, indicating that an increased proportion of instant coffee enhanced polyphenol and flavonoid content.

The antioxidant activity, measured as IC₅₀, followed an inverse trend, where lower IC₅₀ values indicate greater antioxidant potential. Instant coffee exhibited the strongest antioxidant activity (IC₅₀: 16.4 ± 0.8 mg/L), while encapsulated cinnamon showed lower activity (IC₅₀: 20.2 ± 0.02 mg/L). The formulated blends displayed significantly higher IC₅₀ values, with F₁ (29.8 ± 0.3 mg/L) and F₂ (31.9 ± 0.2 mg/L) demonstrating reduced antioxidant potential. However, the difference between F₁ and F₂ was not statistically significant, suggesting that further increasing the proportion of instant coffee in the formulation did not substantially enhance antioxidant capacity.

These findings indicate that instant coffee is the primary contributor to the polyphenolic and flavonoid content in the formulations, significantly influencing their bioactivity. The results further suggest that while blending with encapsulated cinnamon alters the overall composition, it does not enhance antioxidant potential proportionally.

Table 02. Results of Chemical properties of developed instant coffee, encapsulated cinnamon powders and developed formulations

	Instant coffee	Encapsulated cinnamon	F1 (50%-50%)	F2 (60%-40%)
Total phenolic content (TPC) (GAE)mg/g	57.7 ± 0.06a	11.9 ± 0.01d	35.0 ± 0.06c	46.8 ± 0.05b
Total flavonoid content (TFC) (QE)mg/g	63.6 ± 0.1a	11.7 ± 0.005d	59.0 ± 0.044c	62.5 ± 0.1b

Antioxidant Activity (IC50) (mg/L)	16.4 ± 0.8c	20.2 ± 0.2b	29.8 ± 0.3a	31.9 ± 0.2a

#Each value in the table represents the mean ± SD (n=3). Means within each column sharing a different superscript are significantly ($\alpha=0.05$) different at 95% confidence.

Encapsulation and Antioxidant Retention

It is well-documented that microencapsulation helps protect sensitive bioactive compounds, such as polyphenols and flavonoids, from degradation caused by environmental factors like oxygen, heat, light, and moisture during processing and storage (Jafari et al., 2008; Mahdavi et al., 2016). This protection mechanism enhances the stability and potential shelf life of antioxidants. In the present study, although the encapsulated cinnamon showed lower antioxidant activity than instant coffee, the relatively high encapsulation efficiency (95.6%) indicates effective entrapment of antioxidant compounds. The slightly reduced antioxidant activity may be attributed to a dilution effect due to the use of maltodextrin as a wall material. However, the encapsulation process likely prevented further degradation of thermolabile phenolics during spray drying, supporting its utility in preserving functional properties. Future storage studies may further confirm antioxidant retention over time, which has been emphasized in similar studies using plant-based antioxidants (Shahidi and Han, 1993; Tonon, Grosso and Hubinger, 2011).

Sensory Evaluation

The sensory evaluation results for the three formulations are presented in Table 03. The assessed attributes included color, texture, aroma, acidity, flavor, and overall acceptability, measured using a 7-point hedonic scale. Statistical analysis was performed at $\alpha = 0.05$, with different superscripts indicating significant differences within each attribute. The color and texture scores did not show significant differences ($p > 0.05$) among the samples. This suggests that the addition of encapsulated cinnamon, regardless of concentration, did not significantly alter the visual perception or mouthfeel of the coffee. A significant difference was observed in aroma perception ($p < 0.05$). The control (6.0^a) and F₂ (6.0^a) received significantly higher scores than F₁ (5.0^b), indicating that F₂ (40% cinnamon) maintained an aromatic profile similar to the control, while F₁ (50% cinnamon) exhibited a reduced aroma perception. The lower aroma score for F₁ may be attributed to a masking effect from the increased encapsulated cinnamon content, which could suppress some of coffee's characteristic volatile compounds. A significant difference was found in acidity perception ($p < 0.05$). F₂ (5.7^a) had the highest acidity score, significantly higher than F₁ (4.3^b) and the control (5.0^{a,b}). This suggests that a higher coffee proportion (60%) enhanced acidity perception, whereas the increased cinnamon content in F₁ (50%) may have moderated this effect. The presence of bioactive compounds in cinnamon might have influenced acidity perception by buffering some of coffee's natural acids. Significant differences were observed in flavor perception ($p < 0.05$). The control (5.0^a) and F₂ (5.0^a) received significantly higher scores than F₁ (4.0^b). This suggests that a 40% cinnamon content (F₂) allowed for better flavor integration, whereas the higher cinnamon concentration in F₁ (50%) may have altered the expected coffee profile in a less favorable way. The overall acceptability scores showed a significant preference for F₂ (6.0^a) over both the control (5.0^b) and F₁ (5.0^b) ($p < 0.05$). This suggests that a 40% cinnamon content resulted in the most balanced and well-received formulation, whereas increasing the cinnamon content to 50% did not enhance consumer preference. The results demonstrate that encapsulated cinnamon significantly affects aroma, acidity, flavor, and overall acceptability, while color and texture remain unchanged. The 40% cinnamon formulation (F₂) was the most preferred, achieving the highest scores for aroma, acidity, flavor, and overall acceptability, while maintaining a sensory profile similar to the control. The reduction in aroma and flavor scores for F₁ suggests that increasing cinnamon content to 50% led to a sensory imbalance, possibly due to the overpowering effect of encapsulated cinnamon on coffee's volatile aromatic compounds. Additionally, F₂'s significantly higher acidity score suggests that a 60% coffee concentration enhances acidity perception, likely due to the stronger presence of coffee's organic acids. These findings align with previous research indicating that spice incorporation must be carefully balanced to optimize sensory appeal. The encapsulation process may have played a role in preserving cinnamon's bioactive compounds, but its effectiveness depends on concentration and formulation ratios.

Table 03. Results of Friedman Test and Mann-Whitney U Test for Sensorial Attributes (Color, Texture, Aroma, Acidity, Flavor, and Overall Acceptability) of Developed Instant Coffee Formulations

	Color	Texture	Aroma	Acidity	Flavor	Overall acceptance
Instant coffee (499)	6.0 ^a ±1.2	5.1 ^a ±1.6	6.0 ^a ±1.2	5.0 ^{a,b} ±1.6	5.0 ^a ±1.3	5.0 ^b ±1.4
F ₁ (545)	5.3 ^a ±1.4	4.7 ^a ±1.5	5.0 ^b ±1.3	4.3 ^b ±1.6	4.0 ^b ±1.6	5.0 ^b ±1.6
F ₂ (234)	5.7 ^a ±0.9	4.9 ^a ±1.7	6.0 ^a ±1.5	5.7 ^a ±1.6	5.0 ^a ±1.4	6.0 ^a ±1.3

#Rank median within each column sharing a different superscript are significantly ($\alpha=0.05$) different at 95% confidence. Abbreviations: F₁, formulation by 50% instant coffee power with 50% of Encapsulatedd cinnamon power; F₂, formulation by 60% instant coffee power with 40% of Encapsulatedd cinnamon power.

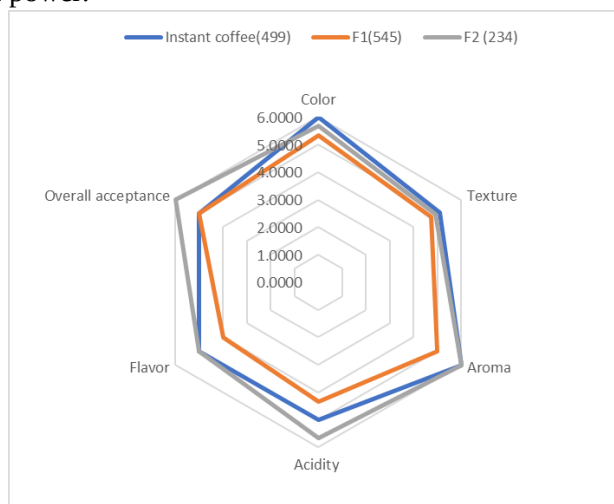


Figure 1. Web diagram relevant to the sensory attributes of samples

F₂ formulation resulted a cinnamon-flavored instant coffee with highly favorable sensory properties. Observed decrease in bioactive compounds in the encapsulated cinnamon powder may be attributable to the dilution effect that occurred during the preparation of the emulsion with maltodextrin as the wall material.

4. Conclusions

The incorporation of microencapsulated cinnamon extract powder into instant coffee enhanced its sensory attributes and overall consumer acceptability. Among the tested formulations, F₂ demonstrated the highest preference in sensory evaluations, indicating its potential as a commercially viable product. Furthermore, the observed higher antioxidant activity, flavonoid content, and total polyphenol content suggest that this formulation can be classified as a functional beverage with potential health benefits. In addition, both non-mixed instant coffee powder and encapsulated instant cinnamon powder exhibit promising potential as standalone products, offering opportunities for further product development in the functional food and beverage industry.

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**INNOVATIVE TECHNOLOGICAL AND MATERIAL
ADVANCEMENTS FOR SUSTAINABLE INDUSTRIAL AND
HEALTHCARE APPLICATIONS**

ICSD 057

INVESTIGATION OF SELF-HEALING CONCRETE USING COCONUT WAX- EPOXY CAPSULES

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Abstract: Self-healing concrete offers a promising and sustainable solution to enhance the durability and service life of cementitious structures, particularly in environments prone to cracking and moisture ingress. This study investigates the effectiveness of coconut wax–epoxy resin capsules as a self-healing agent in concrete. Two capsule formulations with CW:Resin ratios of 1:1 and 1:1.2 were embedded in C20/25 concrete at 2% and 4% dosages by weight of cement, respectively. Concrete cubes (150 mm) were tested at 7 and 21 days for compressive strength, water absorptivity, and tensile strength to evaluate healing performance. The 1:1 capsule mix demonstrated superior results across all tests. Compressive strength increased from 74.56 Pa at 7 days to 191.49 Pa at 21 days. Water absorptivity decreased from 0.13% to 0.12%, indicating reduced porosity and effective sealing of micro-cracks. The 1:1.2 mix also showed improvement, though slightly lower in performance due to possible interference from higher wax content. Tensile strength results aligned with compressive trends, with the 1:1 mix reaching 15.2 MPa at 21 days, outperforming the conventional mix. Capsule survival tests conducted after 24 hours of casting confirmed high integrity, with 88-91% survival in the 1:1 mix and 72-76% in the 1:1.2 mix. These findings support the use of encapsulated healing agents in maintaining structural integrity. Overall, coconut wax-epoxy resin capsules show strong potential for future applications in durable, and self-healing infrastructure systems.

Keywords: Coconut wax; Crack healing; Durability test; Epoxy resin; Self-healing

1. Introduction

The Fresh Concrete Thermal Energy Phase Diagram (FCTEPD) illustrates the acceleration period (3-9 hours) when primary hydration occurs, and the temperature rises to 70°C, leading to thermal fractures in concrete structures (Ribeiro, Yamamoto, and Yamashiki, 2020). These cracks allow harmful substances to penetrate, causing reinforcement corrosion and potential failure (Ferrara et al., 2018; Picandet, Khelidj, and Bellegou, 2009). Repairing these cracks or scheduling maintenance is critical for increasing durability.

However, manual inspection is difficult and costly (Wang et al., 2019). Thus, there is a need for low-cost, high-performance capsules for self-healing concrete to reduce maintenance costs and improve safety (Ferrara et al., 2018; Du et al., 2021). In previous studies, resin microcapsules were made with microcrystalline wax, but coconut wax (CW) offers better biodegradability, environmental impact, and compatibility with concrete (Alqahtani et al., 2020; Omari et al., 2019), making it more suitable for controlled release (Frances et al., 2023; Du et al., 2021). Therefore, this study aims to develop and evaluate a novel coconut wax–epoxy resin capsule system for self-healing thermal cracks in concrete.

1.1 Scope

The acceleration phase (3-9 hours) during which the main hydration reactions take place, where the temperature rises significantly to 70°C, is described in the FCTEPD. Because of that, the investigation was limited to the acceleration phase only. (Mikkelsen and Doster, 2022)

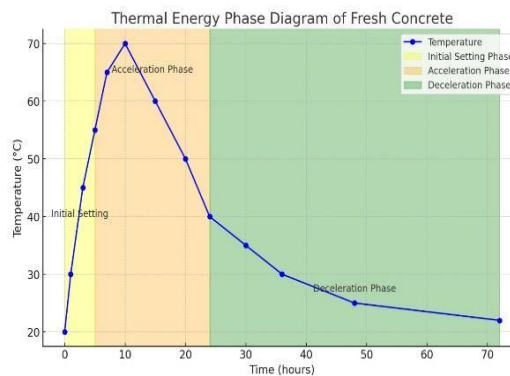


Figure 1: The Fresh Concrete Thermal Energy Phase Diagram

Figure 1. Highlights the main thermal changes that occur during the hydration process, important for managing thermal stresses and ensuring the quality and durability of concrete structures.

In order to obtain the most critical data, this investigation is limited to the tensile and compressive strength and durability tests only (Saidi, Jadidi and Karakouzian, 2022).

2. Literature review

Self-healing concrete has evolved through biological, chemical, and autonomic approaches. Among these, bacterial healing using *Bacillus subtilis* enables calcium carbonate precipitation to seal cracks (Huynh et al., 2022); however, challenges such as bacterial survival, environmental sensitivity, and delayed activation reduce its practical viability (Raza et al., 2023). Autonomic systems, especially microcapsule-based approaches, offer greater control and reliability. In these systems, capsules release healing agents upon cracking, improving response time and overall durability (Roque et al., 2023; Wang et al., 2019). Recent studies have introduced coconut wax–epoxy resin capsules as a natural-synthetic alternative. Coconut wax, a phase change material, can mitigate thermal stress during curing, while epoxy resin provides strong crack bonding (Du et al., 2021; Huseien et al., 2022). These hybrid capsules address the limitations of bacterial systems and show potential to reduce water absorptivity and preserve mechanical strength (Ribeiro et al., 2020). However, comprehensive experimental evaluation of such systems remains limited, particularly under varying environmental and loading conditions. Therefore, this study aims to investigate the feasibility and performance of self-healing concrete incorporating coconut wax–epoxy capsules.

3. Methodology

By reviewing the published literature, it seems that various technical methods are currently used for cracks in concrete.

This study used coconut wax (CW) and epoxy resin to prepare self-healing capsules. The CW used contained fatty acids such as Lauric Acid (45-53%), Myristic Acid (16-21%), and Palmitic Acid (7-10 %) (Suraj, 1850). These acids are commonly esterified, meaning they chemically bind with hardeners (OilCocos, 2024). The epoxy resin used had a melting point of 115°C-120°C.

3.1 Material preparation

This study adopted a laboratory-based experimental method to evaluate the self-healing performance of concrete using coconut wax–epoxy resin capsules. Two capsule formulations were prepared using CW:Resin mass ratios of 1:1 and 1:1.2, following protocols adapted from Du et al. (2021). Coconut wax was heated above its melting point (45°-55°C) for 15 minutes to ensure uniform melting (Figure 2). Liquid epoxy resin (melting point 115°C-120°C) was added as the core material, and the mixture was encapsulated using the melt-diffusion-condensation technique. Capsules were formed by pouring the molten materials into silicone molds, then rapidly cooled and stored at 2°C for 24 hours to achieve solidification. The resulting capsules had a uniform size of approximately **5 mm in diameter**, which is appropriate for homogeneous dispersion in concrete without affecting workability or causing segregation. Capsules were added to C20/25 concrete with a mix ratio of 1:2:4 (cement:sand:coarse aggregate) and a water-cement ratio of 0.4 (Table: 1). The optimal capsule content was 2% (for 1:1) and 4% (for 1:1.2) by mass of cement. Concrete cubes (150 mm × 150 mm × 150 mm) were cast for each mix type. As shown in the Figure 3, the two capsules (resin and hardener) were added when the cube was cast.



Figure 2: Heating coconut wax under laboratory conditions



Figure 3: Photograph of capsules incorporated during sample preparation

A capsule retrieval test was performed 24 hours after casting to assess early-stage integrity. Concrete cubes containing ~330 capsules (1:1) and ~665 capsules (1:1.2) were crushed and sieved through a 2 mm mesh. Intact capsules were visually counted. The 1:1 mix showed a survival rate of 88-91%, while the 1:1.2 mix showed 72-76%. Results align with previous studies (Du et al., 2021; Reda & Chidiac, 2022), confirming that most capsules remained intact after mixing and early curing.

Table 1: Concrete formulation by mass ratio

Ratio (CW: Resin)	1:1	1:1.2
Cement	100	100
Water/cement	0.4	0.4
Capsules	2	4

3.2. Laboratory Experiments

After confirming capsule survival rates, compressive strength (according to BSEN 12390-3:2019), indirect tensile strength test using splitting method under ASTM C496, and water absorptivity test followed ASTM C642 standards were conducted to evaluate the influence of capsules on concrete performance.

4. Results and Discussion

The cubes were placed in the curing tank for 7 days and after 7 days the weight was measured with the absorbed water. Then the cubes were placed in a room temperature and after the water evaporated, the weight was measured again after 24 hours. The same process was carried out on the 21 days cured samples. Each results value was obtained as an average.

4.1 Durability Test

Table 2: Weight of the Cubes (kg)

Parameter \ Sample	Conventional	1:1	1: 1.2
Weight after 7 days of curing	8.251	8.164	8.192
Weight after 24hrs of air-dried sample of 7days cured block	8.064	8.034	8.005
Weight after 21 days of curing	8.377	8.124	5.275
Weight after 24hrs of air-dried sample of 21days cured block	8.098	8.004	8.113

The water absorptivity (Table 2) of the conventional sample increased significantly from 0.187 after 7 days to 0.279 after 21 days, (Figure 1) indicating a notable rise in porosity over time. In contrast, the 1:1 ratio sample showed a slight decrease in water absorptivity, from 0.13 after 7 days to 0.12 after 21 days, reflecting improved material behavior. Similarly, the 1:1.2 ratio sample exhibited a minor reduction in water absorptivity, from 0.167 at 7 days to 0.162 at 21 days. Although the initial absorptivity of this mix was higher than the 1:1 ratio sample, the gradual decrease suggests an improvement in density and highlights the potential effectiveness of the crack-healing mechanism over time.

The decrease in water absorptivity for the 1:1 and 1:1.2 mixes, in contrast to the conventional mix, suggests that the encapsulated epoxy resin has successfully contributed to self-healing within the concrete. The encapsulation method, involving the preparation of the capsules with CW and resin, appears to be effective in reducing porosity by sealing cracks as they form.

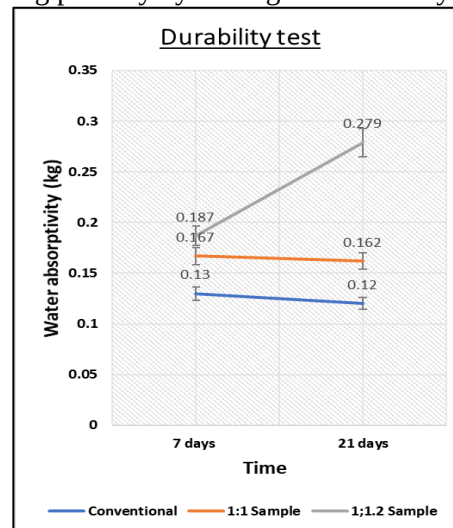


Figure 4: Durability Test Results Variations

This is particularly evident in the 1:1 mix, where the lowest water absorptivity and a decrease over time point to successful crack healing. In the 1:1.2 mix, the decrease, although slight, also supports the hypothesis that the encapsulated resin is filling cracks and improving the matrix's resistance to water ingress. C0 mix, lacking this healing mechanism, shows increased absorptivity, underscoring the effectiveness of the capsule-based approach in enhancing concrete durability. Standard deviation (SD) values were 0.005 and 0.0025 and coefficient of variation (CV) values were 0.004 and 0.015 in 1:1 and 1:1.2 mixtures, respectively.

These findings suggest that the encapsulated self-healing approach is a promising method for improving the long-term durability of concrete, particularly in environments where moisture exposure is a concern. The statistically further reinforces the conclusion that the 1:1 mix provides the most consistent and reliable performance. To identify differences in water absorptivity between the mixes, the SD and CV were calculated. SD measures the spread of values around the mean, with a lower SD indicating more consistent results. CV, calculated as SD/mean, provides a relative measure of variability, allowing for easier comparison between mixes.

An Analysis of Variance test was performed to determine if the differences between the conventional, 1:1, and 1:1.2 mixes are statistically significant. A p-value below 0.05 would indicate that the differences are significant.

4.2 Compressive Strength Test and Tensile Strength Test. (CST and TST)

Table 3: Compressive Strength Test and Tensile Strength Test Results

Sample	After 7days of curing	After 21 days of curing	
	CS (Pa)	CS (Pa)	TS (Pa)
Conventional	136.00	189.10	13.4
1:1	74.56	191.49	15.2
1:1.2	71.28	190.22	14.8

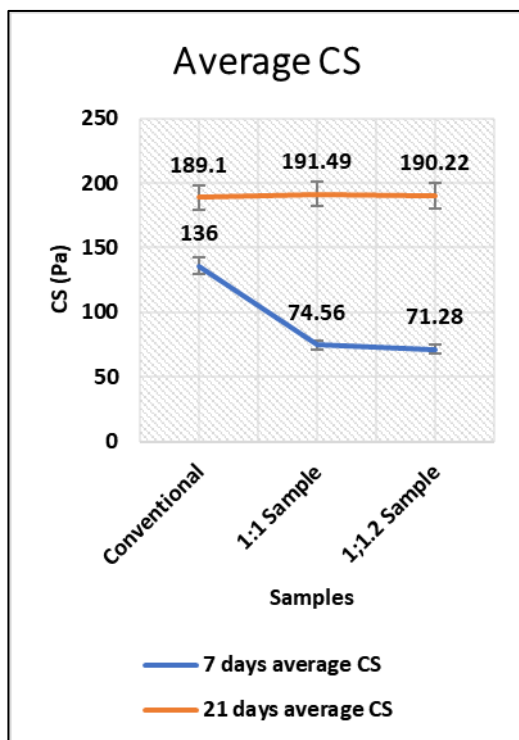


Figure 5: CS Variations

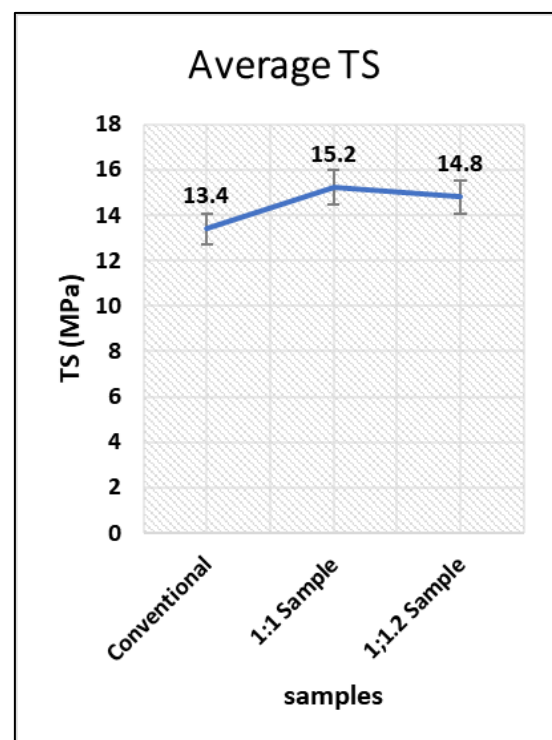


Figure 6 : TS Variations

The CS results reveal distinct trends in the performance of the concrete mixes over time. The conventional mix exhibited expected behavior, (Table.3) due to continued hydration and micro-structural development. In contrast, the 1:1 mix showed an initial CS of 74.56 Pa at 7 days, which was significantly lower than the conventional mix, suggesting that the inclusion of the 1:1 wax-resin capsules initially hindered the concrete's ability to bear compressive loads (Figure 2).

However, the strength of this mix increased sharply to 191.49 Pa at 21 days, surpassing the conventional mix. This improvement suggests that the self-healing capsules became active as the concrete cured, filling micro-cracks and contributing to the development of a denser, stronger matrix.

The 1:1.2 mix followed a similar pattern, with an initial strength of 71.28 Pa at 7 days and a significant increase to 190.22 Pa at 21 days. The slightly lower initial strength of the 1:1.2 mix compared to the 1:1 mix may be due to the higher wax content, which could have affected the initial distribution of the healing agent within the matrix.

Nonetheless, both modified mixes demonstrated effective self-healing and strength gain over time, highlighting the potential of using encapsulated healing agents in concrete.

Tensile strength tests (Figure 3) provide further insights into the impact of self-healing capsules on the concrete's ability to resist tensile forces. Conventional mix recorded a tensile strength of 13.4 MPa after 21 days, serving as a baseline for comparison. The 1:1 mix showed an improvement in tensile strength, reaching 15.2 MPa at 21 days. This increase suggests that the self-healing capsules were effective in mitigating the development of micro-cracks that typically weaken concrete under tensile stress. The 1:1.2 mix also demonstrated enhanced tensile strength compared to the conventional mix, with a value of 14.8 MPa at 21 days, though slightly lower than the 1:1 mix. The slight decrease in tensile strength in the 1:1.2 mix compared to the 1:1 mix could be attributed to the higher wax content, which might have affected the distribution and activation of the healing agent. Overall, the tensile strength results indicate that the inclusion of self-healing capsules improves the concrete's resistance to tensile stresses, likely due to the effective healing of micro-cracks, which are more critical in tensile scenarios. Despite the observed trends, the differences in strength properties between the conventional and modified mixes are not significant at a statistical level.

However, the consistency in compressive and tensile strengths across the mixes suggests that the self-healing process is uniformly effective, contributing to the overall durability and structural integrity of the concrete.

5. Conclusion

The experimental investigation assessed the influence of encapsulated coconut wax–epoxy resin capsules on concrete properties, specifically focusing on compressive strength, tensile strength, and water absorptivity across conventional, 1:1, and 1:1.2 mix ratios. Each sample was tested at 7 and 21 days to evaluate the short- and medium-term self-healing performance.

Table 1: Performance Summary

Mix Type	Water Absorptivity Trend	Water Absorptivity Trend	Tensile Strength Gain	Overall Success (%)
Conventional	49%(0.187 -0.279)	-	Baseline (13.4 MPa)	0% (Baseline)
1:1	(0.13 - 0.12)	88-91%	+13% (15.2 MPa)	~90 - 95%
1:1.2	(0.167 - 0.162)	72-76%	+10% (14.8 MPa)	~85 - 90%

The conventional concrete mix exhibited a noticeable increase in water absorptivity over time, rising from 0.187 at 7 days to 0.279 at 21 days, indicating growing porosity due to ongoing microcracking. In contrast, the 1:1 capsule mix displayed a decrease from 0.13 to 0.12, and the 1:1.2 mix showed a slight reduction from 0.167 to 0.162. This decline in absorptivity suggests that the self-healing capsules effectively reduced internal voids and sealed cracks, especially in the 1:1 mix. The observed reduction of ~36% in water absorptivity compared to the conventional mix highlights the self-healing potential of encapsulated resin.

All mixes showed strength development over time. The **conventional mix** increased from **136Pa (7 days)** to **189.1 Pa (21 days)**, reflecting normal hydration. The **1:1 mix** rose from **74.56Pa** to **191.49Pa**, showing a more significant relative increase and ultimately surpassing the conventional mix. Similarly, the **1:1.2 mix** improved from **71.28 Pa** to **190.22 Pa**. These results indicate that although the capsules may initially reduce strength due to wax presence, their healing action contributes to strength recovery and enhancement at later stages.

At 21 days, the **conventional mix** had a tensile strength of **13.4 MPa**, whereas the **1:1 mix** reached **15.2 MPa**, representing a **13% improvement**. The **1:1.2 mix** also surpassed the control, recording **14.8 MPa**, a **10% increase**. This rise in tensile capacity implies effective healing of microcracks by the capsules, especially under tensile stress, which is more sensitive to crack formation.

A capsule retrieval test conducted after 24 hours revealed that the **1:1 mix achieved a survival rate of 88-91%**, while the **1:1.2 mix showed 72-76%** intact capsules (Table 2). The slightly lower survival in the 1:1.2 mix is attributed to the higher dosage increasing inter-capsule friction and mechanical contact during mixing. These values align with Du et al. (2021), who observed survival rates of 82-93%, and Reda & Chidiac (2022), who highlighted the influence of capsule spacing and dosage on survivability.

Standard deviation (SD) and coefficient of variation (CV) calculations further confirmed consistency in the modified mixes. The **1:1 mix** exhibited an SD of **0.005** and a CV of **0.004**, while the **1:1.2 mix** had an SD of **0.0025** and CV of **0.015**, indicating strong repeatability.

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INVENTION AND INNOVATION

**MACHINE LEARNING FOR EARLY DETECTION OF MOTOR DYSFUNCTION
IN PARKINSON'S DISEASE USING 6-AXIS IMU DATA****N. D. G. T. Nanayakkara¹, K. G. Samarawickrama^{2*}**¹*Industry 4.0 Convergence Bionics Engineering, Pukyong National University, Busan 48513, Republic of Korea.*²*Department of Electrical, Electronic and Telecommunication Engineering,
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Abstract: Parkinson's disease (PD) is a progressive neurodegenerative disorder characterized by distinct motor symptoms such as resting tremor, bradykinesia, muscle rigidity, postural instability and gait abnormalities including shuffling steps, shortened stride lengths, and freezing episodes. The gait impairments severely affect mobility and independence and the general quality of life. Early and accurate identification of PD-associated gait impairment is indispensable for optimal timing of intervention and efficacious management. New developments in wearable sensor technologies have allowed for the non-invasive, real-time measurement of biomechanical parameters of daily activities and the objective quantification of PD-associated gait patterns. This study investigates the effectiveness of traditional machine learning (ML) classifiers in differentiating gait characteristics of individuals with PD from healthy controls using 6-axis inertial measurement unit (IMU) data acquired via Moticon OpenGo smart insoles. This research specifically recognizes the significance of IMU-based features like the angles of roll and pitch, which identify key postural and kinematic patterns of importance in the differentiation of PD-associated gait impairment from normal gait patterns. Three-dimensional accelerations, angular velocities, roll, and pitch angles were assessed based on data collected from Moticon OpenGo smart insoles and subjected to supervising ML techniques such as k-nearest neighbours (KNN), Random Forest (RF) and Gradient Boosting (GB) classification. The results demonstrate that these ML classifiers effectively discriminate between PD and healthy gait patterns, with the RF classifier achieving the highest classification accuracy of 91%. This study highlights the significant role of IMU derived biomechanical features, particularly roll and pitch angles, and underscores the potential of integrating ML techniques with wearable sensor technologies for the early detection and continuous monitoring of PD, thus supporting clinical diagnosis, intervention planning and improved patient care.

Keywords: Biomechanical abnormalities; Inertial Measurement Unit (IMU); Machine learning; Parkinson's disease; Roll and Pitch Angles;

1. Introduction

Parkinson's disease (PD) is a complicated and progressive neurological disorder characterized by cardinal features of resting tremors (shaking), bradykinesia (slowness of movement), muscle rigidity, postural instability (difficulty with balance) and various symptoms associated with motor and non-motor activities such as speech and writing abnormalities (Jankovic and Tan 2020). PD arises when nerve cells in the brain, particularly those responsible for producing the neurotransmitter dopamine, undergo degeneration or loss. Dopamine plays a crucial role in the regulation of smooth and coordinated movement. Thereby it is highly affected to the movement control of the person and cause disturbances to the natural Gait pattern along with disabling motor activities.

This results in notable changes to walking biomechanics specially in both the kinematics and kinetics. PD frequently causes gait cycle abnormalities such as shuffling steps, reduced stride length, shortened steps and difficulty turning. Another phenomenon is known as freezing of gait where individual momentarily feels as the feet are stick to the floor, preventing forward movement. This can occur when attempting to initiate walking or navigating through narrow spaces. Therefore, this leads to disruption to the daily activities, reduce mobility, increase the risk of falls and decrease quality of life (Morris 2000; Jankovic 2008). Therefore, early and accurate identification of Parkinsonian gait patterns is essential for timely intervention, rehabilitation planning, and tracking the progression of the disease.

Recent advancements in Biomedical Engineering field and wearable sensor technology have enabled real-time, reliable and accurate non-invasive methods for human motion capturing and assessment of movement patterns and biomechanics in free-living environments (Porciuncula et al. 2018). These wearable sensors are embedded into foot insoles with inertial measurement units (IMUs) which monitor the three dimensional linear accelerations and angular velocities and plantar pressure sensors which measure the distribution of the insole pressure and variation of force and pressure during gait cycles (Bamberg et al. 2008). With high temporal resolutions, these wearable sensors are well-suited for clinical gait analysis and remote monitoring of PD. With an extensive analysis of these biomechanical data comparing healthy (control) individuals over PD individuals will be a promising tool for extract hidden features which supportive for early identification of PD for clinicians.

With modern world trend, the integration of artificial intelligence, machine learning (ML) and deep learning into healthcare sector has shown great promising outcomes for early diagnosis, smoothen the treatment procedures and management of severity of various diseases. ML techniques have been increasingly applied to classify and interpret complex physiological signal patterns in the context of human motion disorders (Esfahani and Dauwalder 2020; Panicker, Gayathri and Thomas 2021). By learning discriminative patterns embedded in three dimensional biomechanical sensor data, ML algorithms can be trained to classify the individuals accurately between PD and healthy (control) based on the feature analysis.

Therefore, it would be ideal to feed the biomechanical data for ML algorithm training for extract features and assess the patterns of gait abnormalities for early diagnosis of PD. Among various ML algorithms and poses with labelled data, supervised ML models such as k-nearest neighbors (KNN), Random Forests (RF) and Gradient Boosting (GB) have demonstrated strong performance in biomedical classification tasks due to their robustness to noise and capability to model nonlinear relationships (Navita et al. 2025; Zhao et al. 2025).

In this study, we investigate the use of ML classifiers to distinguish PD gait cycle over healthy (control) gait cycle using wearable sensor data. This study explores the application of ML classifiers to differentiate the gait cycles of individuals with PD from those of healthy (control) using wearable sensor data. By leveraging data collected through advanced wearable sensors, which capture key

biomechanical parameters such as accelerations and angular velocities in X, Y and Z dimensions, roll and pitch were used for the current study analysis.

We aim to identify differentiative features which can reliably distinguish between PD associated gait abnormalities and healthy (control) associated gait patterns. Through this investigation, we seek to assess the potential of ML-based classification models in detecting subtle gait alterations that may serve as early indicators of PD, thus facilitating timely clinical remedies and interventions. The analysis employs various supervised learning algorithms, which are trained on labeled datasets to evaluate the accuracy and robustness of gait pattern recognition for clinical applications.

The primary objective of this research is to evaluate the effectiveness of RF, GB, and KNN classifiers in distinguishing PD from healthy (control) gait using participant-level stratified data. The results demonstrate the capability of classification, where the RF have shown the highest accuracy among the selected three ML algorithms for the current study. With these promising outcomes of the ML models can be used as supportive tool for clinicians to diagnose presence of PD in an individual and interpret the impact of the hidden features revealed through the ML models for the better understanding of the complex physiological behavior related to PD.

2. Methodology

This study utilized a previously published dataset collected and curated by the Biomedical Informatics and eHealth Laboratory, Department of Electrical and Computer Engineering, Hellenic Mediterranean University, Estavromenos, Heraklion, Greece (Tsiouris 2021). The dataset comprised of healthy elderly walking IMU data and plantar pressure data from a total of 14 healthy (control) individuals and 7 patients diagnosed with PD. Each subject was instructed to walk along a 10m straight path, perform a 180-degree turn and return to the starting position. Each participant forward walk (trial 1) and return walk (trial 2) were considered as separate trials for the current study analysis. The walking task was aligned with clinical evaluation protocols based on the Movement Disorder Society Unified Parkinson's Disease Rating Scale (MDS-UPDRS), ensuring standardized motor performance assessment. Data acquisition was performed using Moticon OpenGo sensor insoles, enabling the simultaneous collection of inertial signals (acceleration, angular velocity) and plantar pressure across both feet. For each subject, tri-axial acceleration and angular velocity data were collected separately for the left and right foot using the Moticon OpenGo insoles.

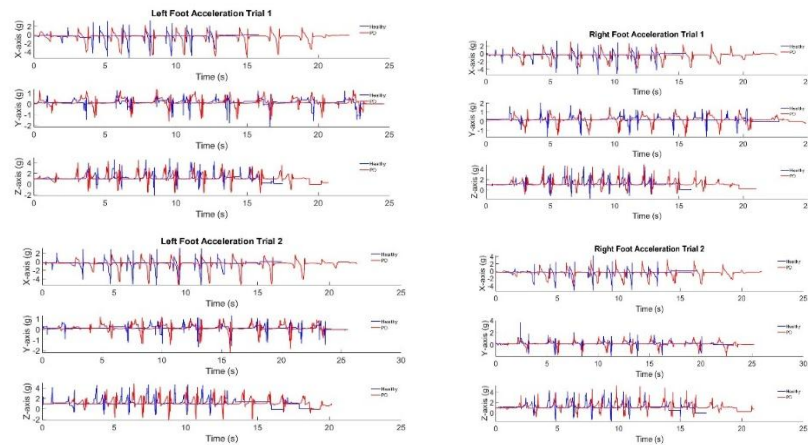


Figure 1: Comparison of IMU data between PD Vs Healthy (control): Left foot acceleration (X,Y,Z) and Right foot acceleration (X,Y,Z) for Trial 1 and Trial 2

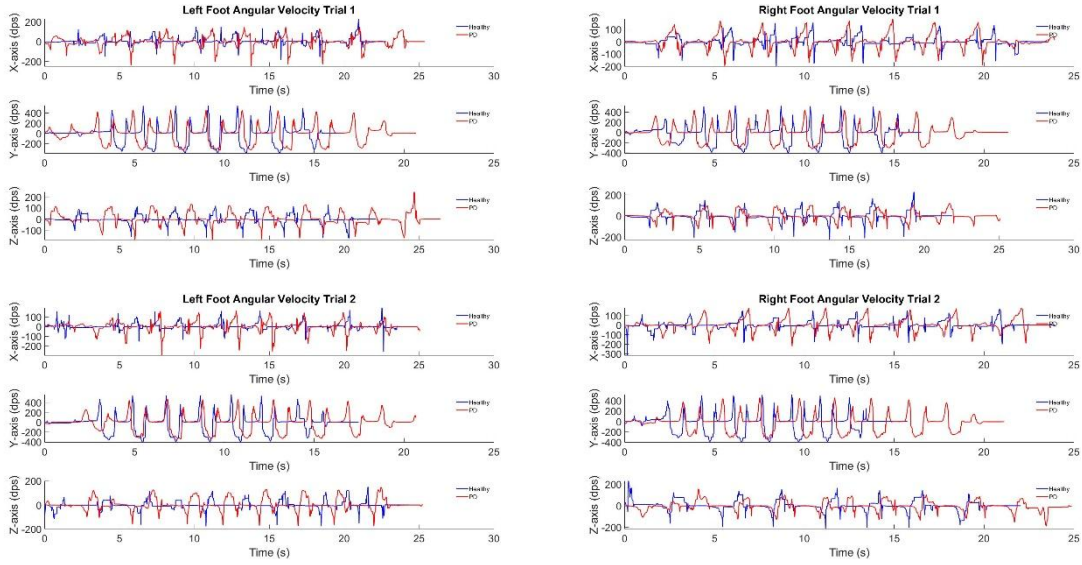


Figure 2: Comparison of IMU data between PD Vs Healthy (control):
Left foot angular velocity (X,Y,Z) and Right foot angular velocity (X,Y,Z) for Trial 1 and Trial 2

To qualitatively assess the signal characteristics of PD Vs healthy (control) gait, IMU data were extracted from each individual test subject and visually inspected for outliers. Thereby, 1 healthy (control) and 2 PD test subject data were excluded from further analysis. Residual data were categorized into healthy (control) and PD, then separated forward walk (trial 1) and return walk (trial 2) data. For each trial, the mean plots were generated using the dynamic time warping techniques to synchronize and retain the gait patterns in IMU data. Comparison mean plots of PD Vs healthy (control) three dimensional acceleration and angular velocities are depicted in Figure 1 and Figure 2 respectively.

The orientation of the foot coordinate system, where the roll angle refers to rotation around the X-axis (inversion/eversion) and the pitch angle corresponds to rotation around the Y-axis (dorsiflexion/plantarflexion). These angular components are derived from equations (1) and (2) where the inertial signals recorded by the IMU sensors embedded in the Moticon OpenGo insoles and serve as key features in capturing postural and kinematic patterns during gait. Furthermore, the orientation angles of roll and pitch plots for a single gait cycle is shown in Figure 3. The extended roll and pitch variations for both trials are depicted in Figure 4.

Visual inspection suggests that the healthy subject demonstrates more regular, periodic signals with higher symmetry between limbs. In contrast, the PD subject's signals appear less consistent, with more variation in waveform morphology and inter-limb asymmetry. These observations are consistent with motor irregularities reported in PD gait literature but are used here solely to motivate subsequent machine learning-based classification and are not presented as diagnostic findings.

$$\theta_{roll} = \text{atan} \left(\frac{AccY}{\sqrt{Acc^2X + Acc^2Z}} \right) \quad (1)$$

$$\theta_{pitch} = \text{atan} \left(\frac{-AccX}{\sqrt{Acc^2Y + Acc^2Z}} \right) \quad (2)$$

3. Feature Extraction and Machine Learning

In the current study, 16 distinguish features namely: 1. Left foot Acceleration X[g], 2. Left foot acceleration Y[g], 3. Left foot acceleration Z[g], 4. Left foot angular velocity X[dps], 5. Left foot angular velocity Y[dps], 6. Left foot angular velocity Z[dps], 7. Right foot Acceleration X[g], 8. Right foot acceleration Y[g], 9. Right foot acceleration Z[g], 10. Right foot angular velocity X[dps], 11. Right foot angular velocity Y[dps], 12. Right foot angular velocity Z[dps], 13. Left Roll, 14. Left Pitch, 15. Right Roll and 16. Right Pitch from each individual biomechanical IMU data were extracted to ML algorithm training and validation. Then each of these biomechanical IMU data signals.

The primary objective of this work was to develop a robust binary classification model capable of distinguishing between PD and healthy (control) gait patterns using ML techniques. Initial preprocessing involved converting group labels into binary format (PD = 1, healthy (control) = 0) and ensuring the removal of missing or non-numeric values. Feature extraction focused solely on quantitative inertial signals. To avoid data leakage and ensure participant-level independence between training and test subsets, a stratified split was applied at the subject level. Specifically, 80% of the subjects were allocated to the training set, and the remaining 20% were reserved for testing. This approach preserved the inter-subject variability while maintaining class balance across partitions.

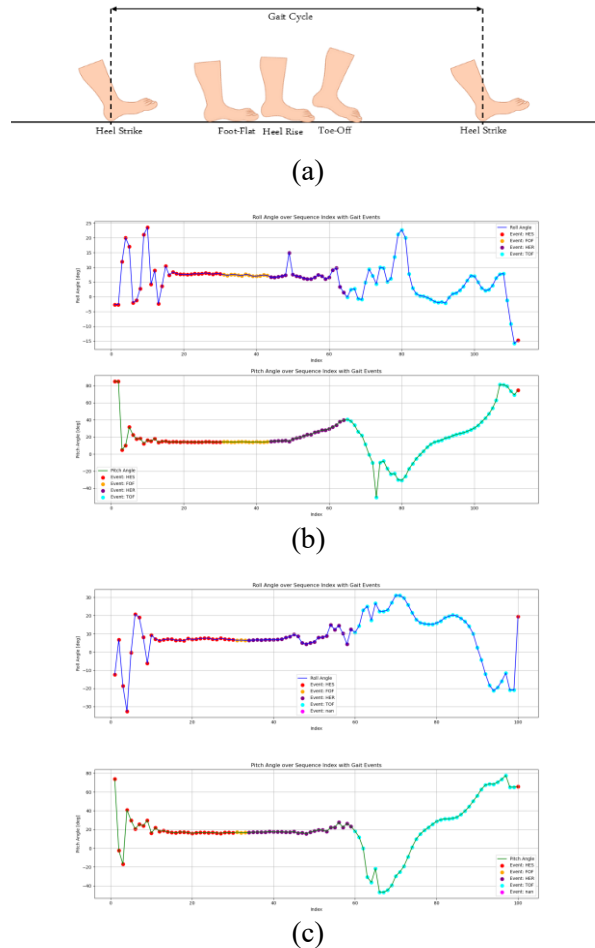


Figure 3: Comparison of orientation data between PD Vs Healthy (control):

(a) Animation of a Gait Cycle

(b) Roll and Pitch variations on PD on a single Gait cycle

(c) Roll and Pitch variations on Healthy (control) on a single Gait cycle

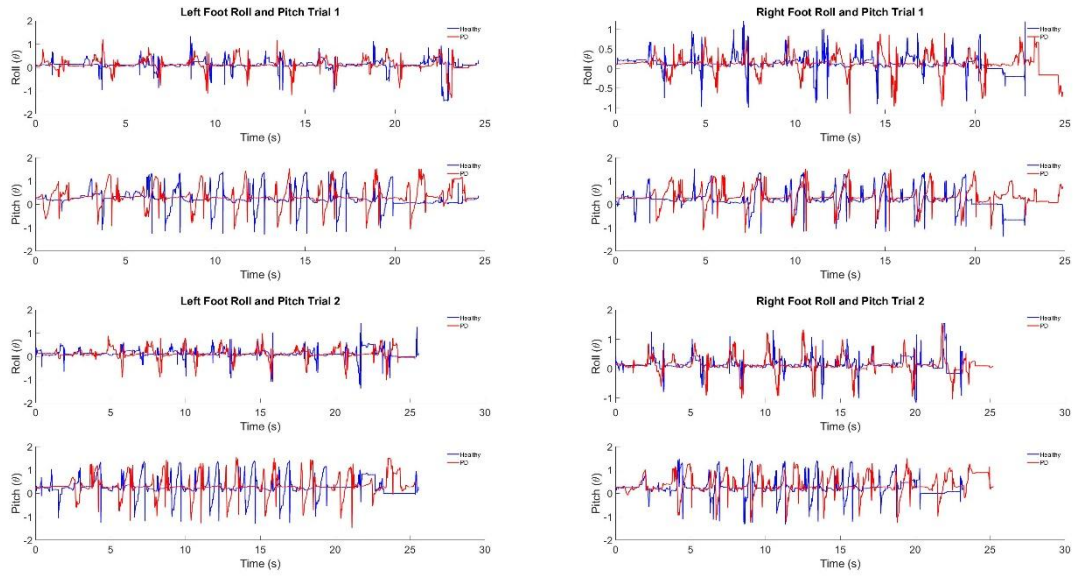


Figure 4: Comparison of IMU data between PD Vs Healthy (control):
Roll and Pitch variations for Trial 1 and Trial 2

The RF classifier was first employed as the baseline model. The features used for training included multi-axis acceleration and angular velocity signals derived from both left and right insoles. The model was trained using scikit-learn's RandomForestClassifier with default hyperparameters and a fixed random seed for reproducibility. Subsequently, GB and KNN classifiers were also trained under identical data conditions to facilitate comparative evaluation. Performance was assessed using standard classification metrics accuracy, precision, recall, and F1-score alongside a confusion matrix to provide insight into classification fidelity at the class level.

4. Results

The RF classifier achieved perfect discrimination on the training set with an accuracy of 1.00. On the held-out test set, the model maintained high generalization capability, achieving a test accuracy of 0.91. The confusion matrix depicted in Figure 5 indicated that 2,356 true negatives (correctly identified healthy (control) samples) and 1,900 true positives (correctly identified PD samples), with only 398 false positives and 24 false negatives. These results indicate strong sensitivity and specificity of the model in distinguishing PD gait characteristics from healthy (control) gait.

The classification report further confirmed the model's robustness, yielding precision and recall values exceeding 0.90 for both classes. These findings suggest the Random Forest model effectively captured the dynamic gait variability associated with PD, likely due to its ability to handle complex feature interactions across multiple time-series channels.

Comparative analysis, as shown in Figure 6, demonstrated that GB achieved comparable but slightly lower performance across all metrics, while KNN significantly underperformed with an average F1-score of 0.68. This decline in KNN performance may be attributed to its sensitivity to feature scaling and inability to generalize well in the presence of intra-class gait variability.

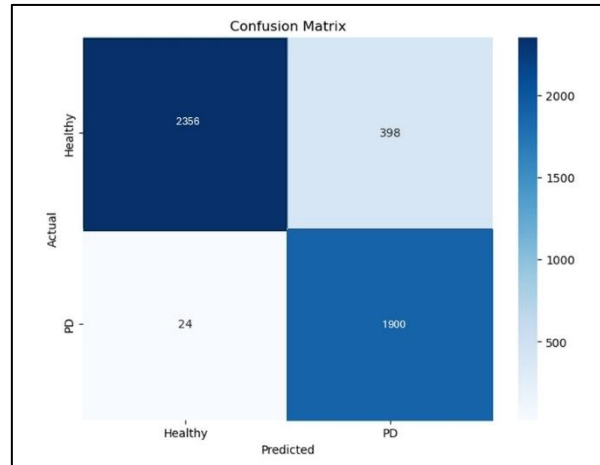


Figure 5: Confusion Matrix for Random Forest between PD Vs Healthy (control)

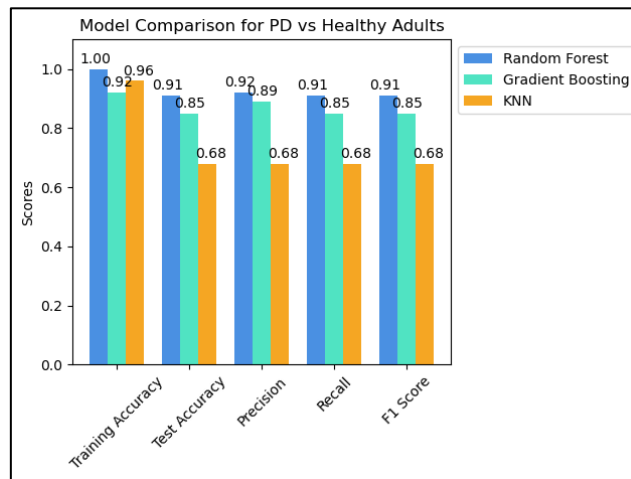


Figure 6: Machine Learning Model comparison between PD Vs Healthy (control)

Overall, the results of this study validate the feasibility of utilizing wearable IMU and pressure sensors, in conjunction with ensemble machine learning techniques, to accurately identify Parkinsonian gait abnormalities. The combination of these advanced sensor technologies and sophisticated data analysis methods provides a robust framework for distinguishing between the motor patterns of individuals with PD and healthy (control). Wearable IMUs and pressure sensors enable non-invasive, real-time monitoring of gait, capturing critical biomechanical parameters such as linear accelerations, angular velocities, and plantar pressure distributions across the gait cycle. These sensors provide high temporal resolution, which is essential for detecting subtle gait disturbances that are characteristic of PD, such as reduced stride length, shuffling steps, and freezing of gait.

The ensemble machine learning models employed in this study, specifically RF, demonstrated high accuracy in classifying gait abnormalities, showcasing their ability to handle noisy, high-dimensional data while capturing complex, nonlinear relationships. This performance highlights the potential of using ensemble methods to improve classification reliability in the presence of heterogeneous data, a common challenge in clinical gait analysis. Furthermore, the subject-level stratification and feature-focused classification approach adopted in this study offers an effective methodology for analyzing individual gait patterns, enabling the identification of nuanced differences between PD and control groups.

Looking ahead, the methodology presented here can be extended to larger cohorts or multimodal datasets, incorporating additional features such as physiological data, environmental context, or video-based motion analysis. Such extensions could provide deeper insights into the progression of PD and enhance the generalizability of the model across diverse populations. Moreover, the integration of these techniques into larger-scale clinical research could facilitate the development of more personalized and accurate diagnostic tools, leading to better disease monitoring, timely interventions, and improved patient outcomes. The adaptability of this approach offers exciting possibilities for advancing the field of clinical gait analysis and contributing to the broader goal of improving care for individuals with PD.

3. Conclusion

In this study, we explored the use of ML classifiers to distinguish between the gait cycles of individuals with PD and healthy (control) using IMU sensor data. Among the various supervised ML models tested, including KNN, RF and GB. Among these ML models, the RF classifier demonstrated the highest accuracy of 0.91 in classifying PD-associated gait abnormalities. This superior performance is attributed to RF's ability to effectively handle noisy data and model complex nonlinear relationships inherent in the biomechanical sensor data. The results underscore the potential of RF as a robust and reliable tool for the early detection and monitoring of Parkinson's disease through gait analysis. Given its high accuracy and versatility, RF can serve as a valuable aid in clinical settings for diagnosing PD and assessing the progression of the disease. Future studies can further refine these models and explore their integration into real-time diagnostic systems to enhance clinical decision-making and patient care.

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IDENTIFYING OPTIMAL VEGETATION INDICES AND REMOTE SENSING METHODS FOR ACCURATE YIELD PREDICTION IN SRI LANKAN TEA PLANTATIONS: A SYSTEMATIC REVIEW

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Abstract: The tea industry has been a key part of Sri Lanka's economy since the British introduced it in 1824 and James Taylor began its commercial establishment in 1867. Accurate yield prediction is crucial for optimizing tea production in Sri Lanka, where low replanting rates, pest and disease outbreaks, climate variability, soil conditions, and agronomic practices significantly challenge yields. In 2020, Sri Lanka's tea production was estimated at 278.48 million kilograms, with a yield of approximately 1,550 kg per hectare. Still, the industry faces a yield gap of 15-20% due to inefficiencies. To address these challenges, modern precision agricultural technologies such as thermal, multispectral, and hyperspectral imaging, Internet of Things IoT integration, and machine learning can enhance crop monitoring, optimize resource use, and improve yield estimation. Based on the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) methodology, English language articles were selected for the analysis using ResearchGate and Google Scholar databases, employing search terms like “Tea Yield Prediction, Machine Learning, Vegetation Indices, Remote Sensing” with Boolean operators AND/OR. This review explores the most effective vegetation indices, such as NDVI, remote sensing platforms, and machine learning models like Random Forest (RF), eXtreme Gradient Boosting (XGBoost), Support Vector Machines (SVM), and Artificial Neural Networks (ANNs). Among these, RF is identified as the most suitable technique, achieving prediction accuracies of up to 90%. Furthermore, studies show that UAV-based remote sensing is more accurate than satellite imagery, with precision improvements of up to 30% due to better temporal resolution and reduced cloud cover interference. A comprehensive SWOT (Strengths, Weaknesses, Opportunities, and Threats) analysis highlights the benefits of remote sensing integration, such as enhanced predictive capabilities and automation, while addressing challenges like high computational costs and data processing. This study concludes by exploring future research opportunities, including real-time monitoring systems, AI-driven decision support tools, and policy recommendations to promote sustainable tea cultivation and advance precision agriculture in Sri Lanka.

Keywords: Machine Learning; Remote Sensing; Tea Yield Prediction; Vegetation Indices

1. Introduction

Sri Lanka is a small island nation with an economy based on agriculture, with a significant amount of its population (27.1%) working in agriculture (Edirisinghe et al., 2024). The Sri Lankan tea industry encounters several challenges, such as a lower replanting rate, a higher cost of production, climate change impacts, pest and disease infestations, labor shortage, and a lack of accurate, real-time data on crop health (Thushara, 2015). These factors directly and indirectly affect both the yield and profitability of the tea industry (Thushara, 2015). Yield prediction is very important in food production. Implementing yield prediction models can help mitigate these challenges by providing useful insights for better decision-making while optimizing the use of resources such as labor, fertilizers, and water, enabling adaptive responses to changing climate conditions, and serving as an early warning system for pests and diseases (He et al., 2023).

Traditional methods like Linear regression, which establishes relationships between yield and factors like rainfall, temperature, elevation, and soil nutrients, and Time series analysis, which uses historical crop yield data to predict future trends of the yield, are the most common crop yield prediction methods (Ansarifar et al., 2021). More recently, machine learning methods such as Artificial Neural Network (ANN), decision trees, association rule mining, and multivariate regression have been applied when predicting crop production.

Remote sensing models are an effective method for yield prediction. A comprehensive overview of the crop is provided by remote sensing data captured by satellites, airplanes, or Unmanned Aerial Vehicles (UAVs) (Joshi et al., 2023). Key Vegetation Indices (VIs), such as Normalized Difference Vegetation Index (NDVI), Enhanced Vegetation Index (EVI), Transformed Vegetation Index (TVI), Soil Adjusted Vegetation Index (SAVI), Visible Atmospherically Resistant Index (VARI), Green Normalized Difference Vegetation Index (GNDVI), Difference Vegetation Index (DVI) and Leaf Area Index (LAI), which are highly connected with biomass and photosynthetic activity, can be detected by multispectral and hyperspectral sensors (Phan et al., 2020). Multispectral imaging, in particular, provides early insights into crop health and growth, so it allows farmers to plan harvesting and labor allocation more effectively. Also, it leads to higher profitability and better export quality (He et al., 2023). By monitoring crop health through multispectral imaging, farmers can optimize fertilizer and irrigation use, reducing unnecessary costs and improving sustainability. Also, it can detect plant stress early, serving as a warning system for pests and diseases, thus preventing crop losses (Luo et al., 2024). By leveraging such advancements, Sri Lanka's tea industry can enhance productivity, ensure sustainability, and regain its competitive edge in the global market.

Furthermore, thermal imaging contributes to determining the level of water stress, and Synthetic Aperture Radar (SAR) permits monitoring in the absence of cloud cover or daylight restrictions (Nugroho et al., 2025). By examining previous trends and current field conditions, remote sensing data combined with machine learning algorithms can improve the precision of yield predictions (Joshi et al., 2023).

This study evaluates how effectively significant vegetation indices like NDVI, EVI, TVI, and LAI predict tea yield when used with remote sensing technology. It examines the applicability of several techniques, such as hyperspectral imaging, UAV (drone)-based sensors, and satellite imaging, especially concerning Sri Lankan tea estates. The study also identifies implementation-affecting practical issues such as cloud cover, limitations in geographical resolution, and cost limitations. Major tea-growing areas like Nuwara Eliya, Uva Province, and Kandy are the focus of the geographical analysis, which ensures that the suggestions are appropriate for Sri Lanka's particular agroclimatic circumstances (Thushara, 2015; Siegmann et al., 2019). To keep the scope clear and focused, non-tea crops and non-remote sensing techniques have been deliberately excluded. In the final phase, the review aims to provide a comprehensive guide for researchers, agronomists, and plantation managers who want to

improve the accuracy of agricultural yield predictions by combining vegetation indices and remote sensing methods in the most effective manner.

2. Tea Cultivation in Sri Lanka: Challenges and Yield Determinants

2.1 Key tea-growing regions in Sri Lanka

Tea (*Camellia sinensis* L.) is a major agricultural product in Sri Lanka. Factors like Sri Lanka's different topography (elevation, slope, and aspect), temperature range, and rainfall determine the areas where tea can be grown and their quality in the particular area (Jayasinghe & Kumar, 2019; Jayasinghe et al., 2020).

Tea plants grow best in areas where the average annual temperature is between 13°C and 28°C and the annual rainfall ranges from 2000 to 5000 mm. These climatic conditions are most suitable for quality and healthy tea growth and optimal tea yields. (Jayasinghe et al., 2019). Also, tea plants can only grow well in certain altitude ranges. In Sri Lanka, low-lying areas (0-100 meters above mean sea level) are not suitable for tea cultivation. The altitude at which tea is grown significantly affects both its quality and yield, meaning that higher altitudes may produce better or different quality tea (Jayasinghe et al., 2020). Also, Sri Lanka's complex geographical diversity creates different wind and precipitation patterns across different regions, resulting in varying climatic conditions. These differences contribute to the unique characteristics/ features of Sri Lankan tea, making its diversity one of its most valuable attributes (Rajapaksha et al., 2017).

Sri Lanka has 6,562,500 ha of land area. From that, currently Tea grown around 221,969 ha, with major tea-growing regions in the Central Province (Kandy and Nuwara Eliya), Uva Province (Badulla, Bandarawela, and Haputale), Southern Province (Galle, Matara, and MulKirigala), and Sabaragamuwa Province (Ratnapura and Kegalle) (Siegmann et al., 2019).

2.2 Factors affecting Tea yields

Several Factors are affecting tea yield, including climatic conditions, soil properties, elevation, and agronomic practices.

Climate change, including erratic rainfall, prolonged dry spells, and high temperatures, makes tea production more challenging. These challenges reduce tea yields and jeopardize the long-term sustainability of the plantation, negatively impacting the people who depend on tea cultivation for their livelihoods (Wang et al., 2018; Guo et al., 2017).

Prolonged drought and high temperatures interfere with the production of essential compounds such as catechins and flavonoids, which are important for tea quality (Guo et al., 2017). In addition, heavy rainfall events damage soil structure, which reduces the availability of nutrients to the roots of tea plants, ultimately reducing tea productivity over time (Sahu et al., 2025). The altitude at which tea is grown significantly affects both its quality and yield, meaning that higher altitudes may produce better or different quality tea (Jayasinghe et al., 2020). Soil fertility, pH, and drainage capacity further affect plant growth, and well-drained, slightly acidic soils are best suited for tea cultivation. Higher water availability significantly increased the growth of new leaves of the tea plant (Ahmed et al., 2014). Also, Long-term chemical fertilizer uses reduced soil pH to 2.82 (severe acidification), lowering tea yield and quality.

2.3 Current challenges in yield estimation and prediction

Accurate yield estimating and prediction is essential for food security and agricultural planning. But there are several challenges to accurate crop yield prediction, such as data limitations, model scalability and integration, environmental uncertainty, and technological issues.

There is a lack of openly accessible crop management data and crop plant physiology data, so current yield prediction models struggle with slight, fragmented datasets on crop management practices (e.g., irrigation, fertilization) (Corcoran et al., 2023). It limits their ability to make accurate predictions across different crops (Meghraoui et al., 2024). Crop yield forecasting involves dealing with unbalanced data sets. Many data sets focus on high-yield scenarios, which leads to biased machine learning predictions. Techniques such as oversampling (artificially increasing underrepresented scenarios) need to be adopted to correct this (Parashar et al., 2024).

Model scalability and integration refer to the ability of yield prediction models to operate across multiple scales (from individual farms to entire regions) and effectively integrate multiple data sources for improved accuracy. Although 78% of the models perform well at the field scale, their accuracy drops by 15-30% when applied to wider landscapes due to unaccounted variables such as pest and disease prevalence, soil and microclimate variability, and topographic changes (slope, elevation, and wind patterns) (Basso et al., 2013).

Environmental Uncertainty is a major challenge when predicting yields. Even with 30 years of historical data sets, extreme weather events (e.g., drought, untimely rain) in machine learning models reduce crop yield forecast accuracy by 20-40% (Corcoran et al., 2023). Under technological issues, when developing a yield prediction model, there is a limitation for satellite data. About 82% of deep machine learning models use satellite imagery to predict crop yields. But distinguishing crop stress signals is challenging due to cloud cover, atmospheric noise, and varying climate conditions (Parashar et al., 2024).

3. Vegetation Indices (VIs)

Table 1: Commonly Used VIs in Agriculture

VIs	Formula	Explanation & Purpose	References
NDVI	$\frac{NIR \text{ (Near Infrared)} - Red}{NIR + Red}$	- Values range from -1 to +1. - Particularly effective in identifying photosynthetic activity. - Measures vegetation health and biomass.	Phan et al. (2021) Zhou et al. (2017)
EVI	$2.5 \times \frac{NIR - Red}{NIR + C1 \times Red - C2 \times Blue + L}$ [C1=6; C2=7.5; L=1]	EVI improves upon NDVI by reducing the effects of atmospheric noise and soil background signals	Lui et al. (2025)
SAVI	$\frac{NIR - Red}{NIR + Red + L} (1 + L)$	- Designed to correct the influence of soil brightness in sparsely vegetated areas. - Particularly useful during early growth stages of crops or in regions with exposed soil.	Kumar et al. (2021) Lui et al. (2025)
VARI	$\frac{Green - Red}{Green + Red + Blue}$	- A digital-camera-friendly VI used in UAV surveys, calculated using RGB bands. - VARI is useful for low-cost crop monitoring	Zhou et al. (2017) Lui et al. (2025)

LAI	-	▪ LAI refers to the total leaf area per unit ground area and is a critical variable in modeling photosynthesis, evapotranspiration, and crop growth. ▪ Often integrated into yield forecasting models and crop growth simulations	Wu et al. (2024) Zhou et al. (2017) Lui et al. (2025)

3.1 Applications of VIs in Cultivation

VIs derived from remote sensing have become vital tools in the monitoring and management of tea (*Camellia sinensis*) cultivation. Their ability to capture spatial and temporal variations in canopy vigor, biomass, and physiological health has enabled significant advancements in precision tea agriculture.

3.1.1 Yield Prediction

One of the most prominent applications of VIs in tea agriculture is the estimation of crop yield. NDVI and other VIs, when combined with Machine Learning (ML) algorithms such as Random Forest (RF), Support Vector Machine (SVM), Traditional Linear Regression Model (TLRM), Extreme Gradient Boosting (XGBoost), and Support Vector Regression (SVR), Voting Regression (VR) and Linear Regression (LR) have been used to predict seasonal and annual tea yields with high accuracy (Phan et al., 2021).

3.1.2 Crop Health and Canopy Monitoring

Table 2: Vegetation Indices used for Tea monitoring

Monitoring Factor / Investigation	VI	ML Method Used	Reference
Seasonal fresh tea yield estimation using Sentinel-2 and UAV imagery	NDVI, EVI, GNDVI, VARI, DVI, etc	RF, Voting Regression, AdaBoost, Lasso-LARS, Gradient Boosting, MLR	Liu et al. (2025)
NDVI, EVI	SVM, RF	RF	Phan et al. (2021)
Monitoring tea leaves and estimating crop yield	NDVI	RF, SVM	Nuraeni & Manessa (2022)
Monitoring tea health and forecasting yield	NDVI	SVM, RF, TLRM	Phan et al. (2021)

4. Machine Learning Models for Tea Yield Prediction

Table 3: Performance and Accuracy of Machine Learning Models when Predicting Tea Yield

Monitoring Factor/Investigation	ML Models Used	Most Accurate ML model	Accuracy	Reference
Climate change impacts on tea yield	Regression models	Multiple Linear Regression (MLR)	70%	Sitienei et al. (2017)
Tea yield prediction using weather, soil, crop, and agro-management data	XGBoost, SVR, AdaBoost, Multi-Layer Perceptron (MLP)	XGBoost	Mean Absolute Error (MAE)= 0.123 t/ha, Root Mean Square Error (RMSE) = 0.154 t/ha	Batool et al. (2022)
Seasonal fresh tea yield estimation using Sentinel-2 and UAV imagery	RF, VR, AdaBoost, Lasso-LARS, Gradient Boosting, MLR	RF (Spring, Summer); Voting Regression (Autumn, Annual)	R ² up to 0.47	Liu et al. (2025)
Yield prediction across seasons	SVM, RF	RF	High accuracy with RF	Phan et al. (2021)
Weather impact on tea production	RF, SVM, MLR, LR	RF	R ² = 0.88	De & Rankothge (2022)
Monitoring tea leaves and estimating crop yield	RF, SVM	RF	72.47%	Nuraeni & Manessa (2022)
Monitoring tea health and forecasting yield	SVM, RF, TLRM	RF	R ² = 0.73	Phan et al. (2020)

5. Ground Truth Data Collection in Tea Yield Prediction

5.1 Definition and Importance of Ground Truth Data

Ground truth data are field-measured values used as benchmarks for model training and remote sensing analysis (Batool et al., 2022). This ground truth data has been shown to minimize model uncertainty and maximize prediction accuracy, especially in heterogeneous tea landscapes where soil and microclimate variability greatly affect tea production (Huang et al., 2021). Precision agriculture techniques can be implemented through ground truthing, which ensures a strong correlation between remotely sensed vegetation indices and field-measured tea yield (Salas et al., 2021). These databases are essential for tea research in Sri Lanka as they validate vegetation indices and ensure the spatial-temporal accuracy of yield forecasting systems (Batool et al., 2022).

5.2 Methods of Collecting Field Data

5.2.1. Yield Measurements

Yield measurement is one of the most important components of ground truth data. Most studies show that they collect tea yield data manually for predicting tea yield. The study Liu et al. (2025) that conducted in Pu'er City, China, manually collected fresh tea yield to calibrate and validate machine learning models for predicting tea yield using remote sensing data. Historical records of tea plucking, including the quantity and quality of leaves harvested, offer direct measurements of yield. In Sri Lanka,

the primary method for yield measurement also remains manual, where harvested tea leaves are directly weighed, and the results are standardized to kilograms per hectare (kg/ha) (De and Rankothge, 2022).

5.2.2. LAI Estimation

The measurement of LAI represents a fundamental biophysical factor that directly influences plant productivity levels. LAI field measurements are performed with instruments like the LAI-2000 and the use of hemispherical photography systems. The yield prediction models utilize LAI as a predictor because it accurately reflects canopy health and photosynthetic capabilities (Wang et al., 2025).

6. SWOT Analysis of Integration of Remote Sensing and Machine Learning in Yield Prediction

6.1 Strengths of Integration of Remote Sensing and Machine Learning in Yield Prediction

The high spatial and temporal resolution of satellite imagery enables frequent and large-scale monitoring of tea plantations in the process of tea yield prediction (Liu et al., 2025). Similarly, machine learning algorithms such as RF and SVM have shown robust performance in optimal yield forecasting, with up to 75% accuracy, while traditional methods work (Nuraeni and Manessa, 2022).

6.2 Weaknesses of Integration of Remote Sensing and Machine Learning in Yield Prediction

The accuracy of machine learning models used in crop prediction can be limited by the quality and quantity of ground truth data. Collecting that data can be both expensive and labor-intensive (Nuraeni and Manessa, 2022). Especially when models are trained on non-standard, limited, and imprecise data, there can be problems with fitting and generalizing the final output (Huber et al., 2024).

6.3 Opportunities for Integration of Remote Sensing and Machine Learning in Yield Prediction

The application of advanced machine learning methods, particularly deep transfer learning, enables knowledge transfer from rich-data regions to regions with limited ground truth as an effective solution for data-poor circumstances (Huber et al., 2024). Cloud computing platforms combined with geospatial artificial intelligence (GeoAI) tools increase accessibility to develop real-time decision support systems that operate at specific site locations, which allows improved management strategies for tea plantations (Nuraeni and Manessa, 2022).

6.4 Threats to the Integration of Remote Sensing and Machine Learning in Yield Prediction

Limited availability and accessibility of high-quality remote sensing and ground truth data due to privacy and ownership issues pose challenges for model development and validation (Huber et al., 2024). Seasonal variations, age of tea plantations, changes in management practices, and environmental factors can affect model performance, which can reduce the reliability of forecasts (Suvasthika et al., 2021). Satellite data can also be affected by cloud cover, solar angle, weather conditions, sensor limitations, and temporal gaps, which can also reduce the reliability of yield forecasts (Das et al., 2021; Thushara, 2015; Liu et al., 2025). The use of external technologies and platforms creates technical and financial problems, and they require high initial investment costs to use the technology (Nuraeni and Manessa, 2022; Huber et al., 2024).

7. Future Perspectives and Research Gaps in Remote Sensing for Yield Prediction in Sri Lankan Tea Plantations

7.1 Advancements in Satellite and UAV Technologies

The use of satellite imagery combined with UAVs has transformed agricultural monitoring by providing high-resolution data essential for yield forecasts (Maimaitijiang et al., 2020). The Sentinel-2B and Landsat-8 OLI satellites provide high-resolution multispectral images, which enhance the monitoring both temporally and spatially of tea plantations. These datasets capture critical features of the canopy, important for modeling tea yields based on fractional canopy cover, enabling accurate assessments of tea crop health and yield (Ramadanningrum et al., 2020).

Recent studies show that UAV-based hyperspectral remote sensing can be used to predict tea plant quality criteria, such as polyphenols and amino acids, and to assess tea plant environmental stress

effects. This marks a significant advancement in precision agriculture and yield prediction strategies (Luo et al., 2024).

7.2 Potential for Real-Time Monitoring and Decision Support Systems

Several critical research gaps must be addressed to fully realize the potential of remote sensing technologies for yield prediction and optimized management in Sri Lankan tea plantations:

- Only a few validation studies are comparing the performance of different VIs such as NDVI, SAVI, and EVI across various tea-growing regions in Sri Lanka. Therefore, there is a need for additional studies in Sri Lanka. These studies will help assess the accuracy of these indices in predicting tea yield under diverse environmental conditions, including soil type, topography, and climatic zones (Mukherjee et al., 2013).
- There is a lack of temporal analysis connecting spectral data to plant physiological changes. The growth cycle of the tea plant requires a thorough analysis linking changes in tea plant physiology with spectral data derived from remote sensing. Such analyses would significantly enhance the accuracy of remote sensing data to predict seasonal tea yields effectively (Kariyawasam et al., 2025).
- Sri Lanka exhibits minimal standardization in UAV data recording. Therefore, studies are needed to develop standardized UAV-based methods to ensure standardization in data collection, including variations in topography, elevation, and plantation density within the country (Mukherjee et al., 2013).
- While there is much research on the benefits of remote sensing technologies in predicting yields in large-scale tea plantations, there is limited research on the cost-effectiveness and accessibility of these technologies for smallholder tea farmers. Future studies should explore the economic feasibility and scalability of UAVs and other remote sensing technologies for use by smallholder tea farmers (Kariyawasam et al., 2025).

8. Conclusion

This review illustrates how precision agriculture methods adopted in other tea-producing countries can be applicable to address the long-standing issue of low yield in Sri Lanka's tea industry. By combining remote sensing technologies with Random Forest machine learning, predictions can be accurate up to 90% of the time. In the realm of remote sensing for agricultural monitoring, aerial drones demonstrate superior capabilities compared to satellite images and provide valuable, detailed, and timely information that is used to closely monitor crops. The literature shows that the NDVI is highly used in tea yield prediction, and also the SAVI and EVI help enhance the accuracy of predictions. Satellite image indices and accurate on-site measurements, with help from machine learning, make up a stable basis for current tea production forecasts.

In the context of tea farming, future studies should focus on real-time monitoring systems and AI-based decision support systems tailored to the farmers' requirements for Sri Lanka. Also, the adoption of policies aimed at promoting smart agricultural practices is equally important for augmenting the competitiveness of the tea industry in Sri Lanka. These shifts could enhance the sustainability and the efficiency of resource optimizations, while further increasing productivity in one of the most important agricultural sectors in Sri Lanka.

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MICROPLASTICS AND PLASTICS: CHALLENGES, INNOVATIONS, AND SUSTAINABLE SOLUTIONS

ICSD 145

**UNDERGRADUATES' AWARENESS AND PERCEPTIONS ON MICROPLASTICS :
A CASE STUDY ON SABARAGAMUWA UNIVERSITY OF SRI LANKA****K.W.R. Himara^{1*}, R.M.K.D. Rathnayake², N.W.J.V. Hansika², N.M.H.I. Nayakarathne²**¹*Department of Agribusiness Management, Faculty of Agricultural Sciences, Sabaragamuwa University of Sri Lanka, Belihuloya, Sri Lanka*²*Department of Export Agriculture, Faculty of Agricultural Sciences, Sabaragamuwa University of Sri Lanka, Belihuloya, Sri Lanka***Correspondence E-mail: ruwandahimara128@gmail.com, TP: +94715726022*

Abstract: Microplastics have raised increasingly crucial environmental and health issues, yet the awareness of undergraduates on this topic remains less explored. Hence, this study investigated the depth of awareness and knowledge of microplastics: among undergraduates in Sabaragamuwa University, focusing on their knowledge of sources of microplastics, environmental consequences, and health risks involved. Data were collected from 154 respondents using a structured online questionnaire through snowball sampling and was analyzed via descriptive analysis. Females form a higher percentage (69.5%) compared to males (30.5%). 91.6% of participants were familiar with microplastics, with knowledge gained primarily through social media (71.4%), university education (50.6%), and news outlets (37.7%). However, misconceptions last, with 28.6% showing limited understanding of primary and secondary microplastics. The primary source of pollution identified is industrial wastewater (72.7%) with other significant sources such as tire abrasion (41.6%) and synthetic textile fibres (53.2%) being less acknowledged. Freshwater pollution (69.5%) was identified as the most severe consequence, followed by soil (61.7%) and marine pollution (60.4%), with less concern for air pollution (49.3%) and climate change (48.7%). 70.8% of the participants have realized that microplastics can lead to respiratory problems, reproductive disorders, and cancer. A significant majority (65.6%) emphasized the need for further research on health impacts. The findings show that a broad understanding of microplastics will have some unique holes relating to sources and health risks. the study delved into the many avenues in which the dialogue on microplastics might be enriched through insights from undergraduates. The study results here will have positive implications on enhancing empowerment among students towards behavior change in a more responsible way towards the environmental dimension environment reduced microplastic pollution.

Keywords: Microplastics; Awareness; Perceptions; Health risks; Environmental consequences

1. Introduction

Microplastics are synthetic materials which have organic origin based polymers just like polyethylene, polyvinylchloride, or polystyrene, and polypropylene. They are characterized by its very small size (≤ 5 mm) and varieties of morphology (Y. Lee et al., 2023). Indeed, these miniature particles, originating from fragmentation and breakdown of larger plastic items into parts or intentionally manufactured as small particles, reflect genuine similarity in shape, composition, and size (Bergmann et al., 2015). The two sources of microplastics are mainly primary microplastics, which are designed to be used in cosmetic and personal care products such as microbeads, and secondary microplastics, which are produced by degradation of larger pieces of plastic waste through natural degradation processes. Morphologically, such include fragments, films, fibers, foam or beads. Irregular shapes such as cubic, spherical, elongated, and rod-like characterize them. Differences in type and molecular structure of these polymers have resulted, so far, in very long degradation periods, which have ended in environmental worries. For microplastics origination, plastic is used for selection in packaging, construction, health care, and agriculture due to easy access and cheap price (Saad et al., 2024). Materials that have physical properties of being lightweight but strong, durable, corrosion and chemical resistant, solid, and insoluble in water form such as those found in Ziani et al. (2023)(Rai et al., 2023).

Lesser rates at which microplastics will biodegrade mean longer residence times within the environment, given their higher stability of chemical structure and resistance to factors present in the environment (H. Lee & Kim, 2018). They are capable of further fragmentating into smaller particles under physical, chemical, or biological forces and have ability to adsorb other contaminants, acting as vectors for pollutants (Padervand et al., 2020). Because of their durability and very low rates of biodegradation, they are well suited for accumulation in aquatic and terrestrial ecosystems. Microplastics can be found in many places, from deep-sea sediments to polar ice and even in distant mountain regions.(Bergmann, et al., 2017) Microplastics induce green house gas emissions from the soil. Airborne microplastics have the potential to aid in cloud formation and interfere with atmospheric cooling. Climate change induced extreme events redistribute microplastics in the environment, causing the pollution to increase vertically and horizontally. (Parvez, et al.2024). Pressing as fresh air, soil, and aquatic environments their presence requires the urgent and serious consideration of this issue exhaustively. Research also highlights that the distribution and concentration of microplastics are influenced by both fragmentation rates and the influx of plastic waste into marine environments. (Matthieu George, et al., 2023)

Worldwide, the last few decades have seen a rise in plastic production, and this has also been the case in Sri Lanka. The country produces roughly 249000 tonnes of plastic waste per year, exposing it to very serious challenges in terms of the sustainable management of such wastes (Central Environmental Authority, 2021). An alarming 67 965 tons, or 27 percent, go uncollected, while it is observed that an estimated 41 percent move into the environment from waste management systems (United Nations Environment Programme, 2022). Studies further reveal that plastics account for 5-7% of municipal solid waste (MSW), with a good portion of this being disposed of in uncontrolled landfills, thereby contributing to microplastic pollution (Mr. Nihal Cooray et al., 2021).It is a university role in educating the society in knowledge and attitude towards the global challenges, including that of microplastic pollution. Undergraduates, as future leaders, researchers and policymakers, make an important population towards educating the importance of awareness and encouraging responsible behavior towards the environment. Their understanding of sources of microplastics, environmental consequences, and health risks will be paramount in shaping how society is to respond to the crisis.

The main objective of this study is to evaluate undergraduates' level of awareness and understanding about microplastics in Sabaragamuwa University of Sri Lanka concerning their knowledge on sources, environmental ramifications and health implications affecting microplastics. Along with this, it looks into how the said awareness affects upon their perception and usage regarding plastics, plastic waste management, and measures taken to reduce microplastic pollution. It is important to understand this

dynamic in order to design targeted awareness programs and interventions for sustainable behavior to promote environmental impacts due to microplastics. The present research ultimately feeds into the discussion of microplastic pollution by providing perspective into the awareness and perceptions of undergraduates at SUSL. It also provides a summary of the role of higher education institutions in nurturing environmental stewardship. The revelations will be a starting point towards policy development for empowering students as catalysts for change so that it adds to the global effort toward mitigating the adverse effects of microplastics.

2. Methodology

This study adopted a descriptive cross-sectional survey, with a view to awareness, attitude, and behavior of undergraduates towards microplastic pollution. This approach was selected to enable the collect of both quantitative and qualitative data for better understanding of the issue. Some establishments of the higher learning institutions, especially undergraduates of Sabaragamuwa University of Sri Lanka, are targeted by the study. A sample of 154 students engaged with this survey through snowball sampling to ensure the coverage of diverse faculties, different academic years, and gender groups. The non-probabilistic method was selected to reach out to participants with varying exposures to environmental issues and other microplastic studies, thereby reducing selection bias and ensuring that the student community was adequately represented. The data collection step was pursued between September 2024 and February 2025. A structured online questionnaire was prepared and proceeded with via Google Forms for enhancing accessibility and broad participation. The questionnaire sought to gather information related to knowledge of microplastics, personal behaviors and attitudes, and educational influence on awareness. The data were analyzed using SPSS Statistics 27 and Microsoft Excel 2021. General trends in knowledge, attitude, and behavior were analyzed using descriptive statistical techniques and reliability test.

3. Results and Discussion

3.1 Sample Demographics

About 83.7% of the respondents formed a group aged 24-26 years, with an age group of 27 and above occupying a small percentage, which is about 3.4%. Females are a large gender segment of the respondents (69.5%), while males account for 30.5%. For residential area respondents, the largest percentage was from the sub-urban area (57.1%), while urban and rural areas stood at the same level, with 33 respondents each (21.4 %).

Table 1. Demographic information of Undergraduates (n=154)

Demographics information	Categories	Percentages (%)
Age	21-23 years	12.9
	24-26 years	83.7
	27 and above years	3.4
Gender	Male	30.5
	Female	69.5
Residential area	Urban	21.4
	Sub-urban	57.1
	Rural	21.4
Year of study	First year	3.89
	Second year	4.5
	Third year	78.6
	Fourth year	12.98

The findings of this study provides invaluable information into the awareness, perceptions, and knowledge gaps among undergraduates concerning microplastic pollution at Sabaragamuwa University. An enormous majority, 91.6% of the respondents, know what microplastics are and find heavy reliance

on social media (71.4%) for this knowledge, followed by university education (50.6%) and news (37.7%). This fact, however, raises concern about how accurate this information is because it could include misinformation and oversimplified narratives that lead to persistent misconceptions.

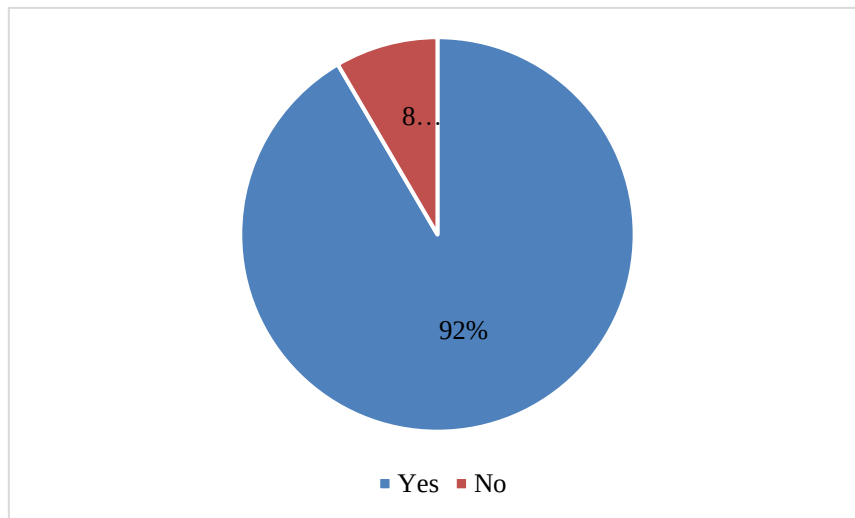


Figure 1: Awareness about Microplastics

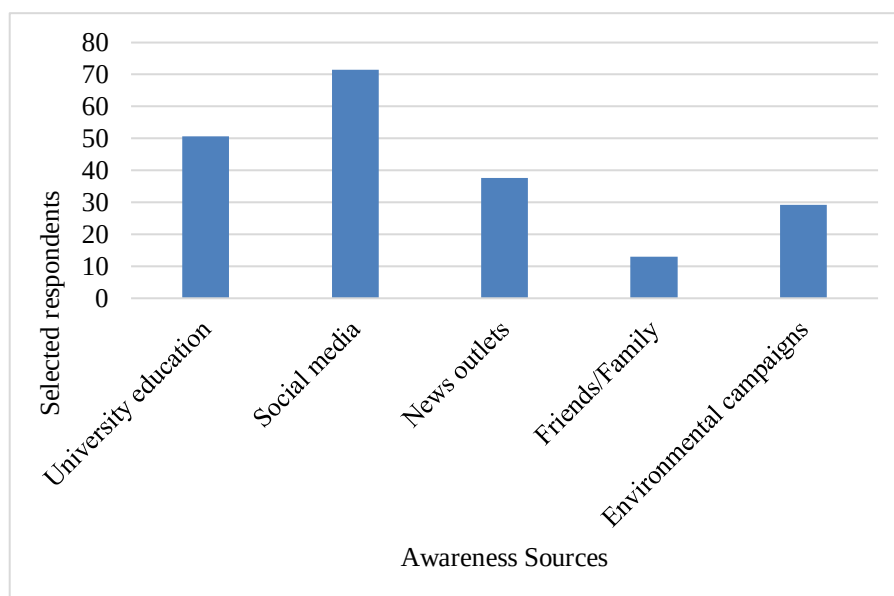


Figure 2: Sources of Awareness on Microplastics

Fewer undergraduates cited environmental campaigns (29.2%) and friends/family (13%). A substantial portion (28.6%) reported limited understanding of types of microplastics (primary and secondary), with a similar percentage (28.6%) indicating only a moderate understanding, suggesting a significant knowledge gap in this area. While understanding of sources of microplastics was relatively better, with the highest percentage (35.1%) reporting moderate understanding, a considerable proportion still demonstrated limited (27.3%) or no understanding (13.6%). For environmental impact of microplastics, responses skewed towards moderate (35.1%) to good (28.6%) understanding, indicating a stronger grasp of this aspect. Health risks associated with microplastics showed a similar trend, with the largest segment reporting moderate understanding (35.7%) and a notable portion demonstrating good

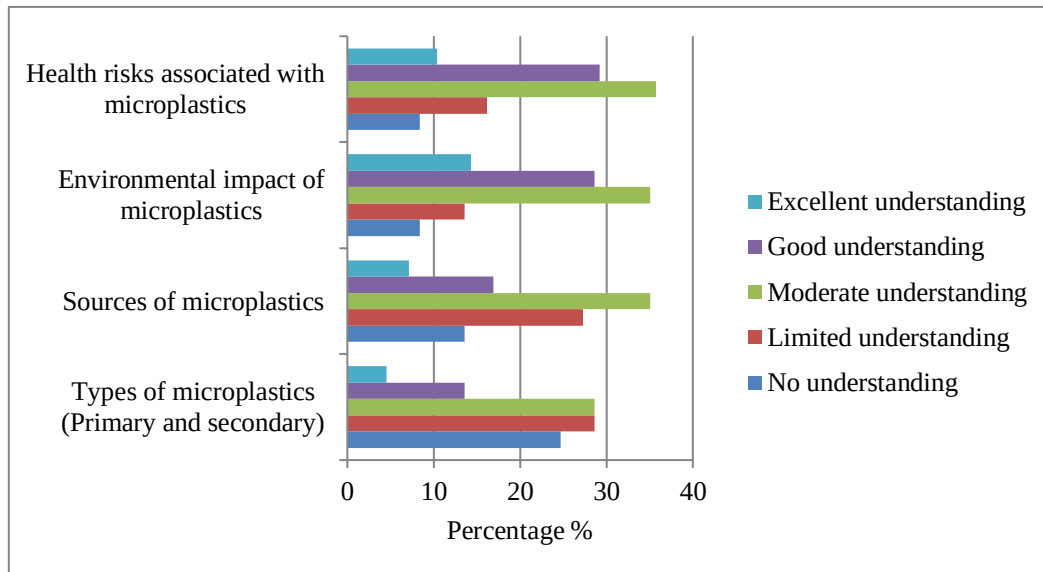


Figure 3: Understanding of microplastic aspects

understanding (29.2%), though limited understanding (16.2%) and lack of understanding (8.4%) were still present. The reliability analysis (Cronbach's Alpha = 0.854) confirms that the 5 point ordinal Likert-scale responses are consistent and valid for interpreting undergraduate knowledge and awareness levels regarding microplastics.

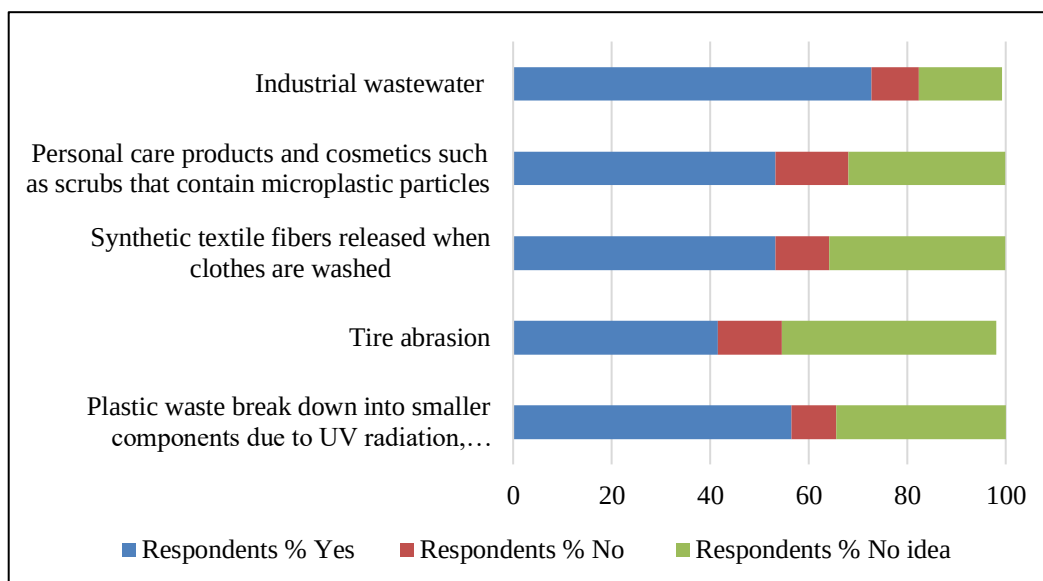


Figure 4: Awareness of actions which add microplastics to the environment

A majority (56.5%) of the respondents have heard that plastic waste can break down into much smaller components. A considerable portion of 34.4% are actually unsure about this; it may indicate a wrong idea or no understanding concerning this process. Awareness was also low for tire abrasion as a source at 41.6%, with nearly half of respondents having no clue (43.5%) as to this source. The pattern observed in the case of synthetic textile fibers is evident here : 53.2% answered in a positive manner while 35.7% were unsure. Though personal care products and cosmetics showed somewhat better (53.2%) awareness, the number of unsure people remained high (31.8%). Industrial wastewater had the highest awareness (72.7%), which means that people seem to know better about this source than others. One of

the most significant gaps in the knowledge was the minimal understanding of the sources of microplastics. While 72.7% of respondents suggested that industrial wastewater would be a primary source, other eminent sources like synthetic textile fibres and tire abrasion were comparatively underappreciated. This may mean that students associate microplastic pollution primarily with industrial processes, thus overlooking other mundane sources like synthetic clothing and emissions from vehicles. Such an educational gap can be filled by engaging students in microplastic education and further addressing their understanding of the wider sources of microplastics.

Microplastics' contribution to environmental harm is assessed by the undergraduate respondents' present knowledge, as illustrated in figure 5. Of the respondents, 69.5% considered the impact of microplastics on freshwater pollution to be high or very high. This is followed by soil pollution, where 61.7% ranked microplastics at a high or very high impact. Microplastics are thought to contribute very high or high to marine pollution by 60.4%. In contrast, regarding air pollution and climate change, the perceptions of microplastics' contribution were relatively low, with 49.3% and 48.7%, respectively, checking these avenues associatively. The lower concern for air pollution and climate change could mean a relative absence of knowledge on how microplastics deter while contributing to these issues, such as through the production and incineration of plastics or release of microfibers into the atmosphere.

The concerns for freshwater pollution, soil contamination, and marine pollution were widely acknowledged, while air pollution and climate change were considered somewhat less worrying. Microplastics' ability to provide a different category of airborne contaminants affecting climate change through the minute perturbations of atmospheric processes, suggests a further need for emerging scientific conclusions to be included in the curriculum for the understanding of microplastics in full spectrum. The reliability analysis (Cronbach's Alpha = 0.917) confirms that the ordinal Likert-scale responses are consistent and valid for interpreting environmental harm caused by microplastics.

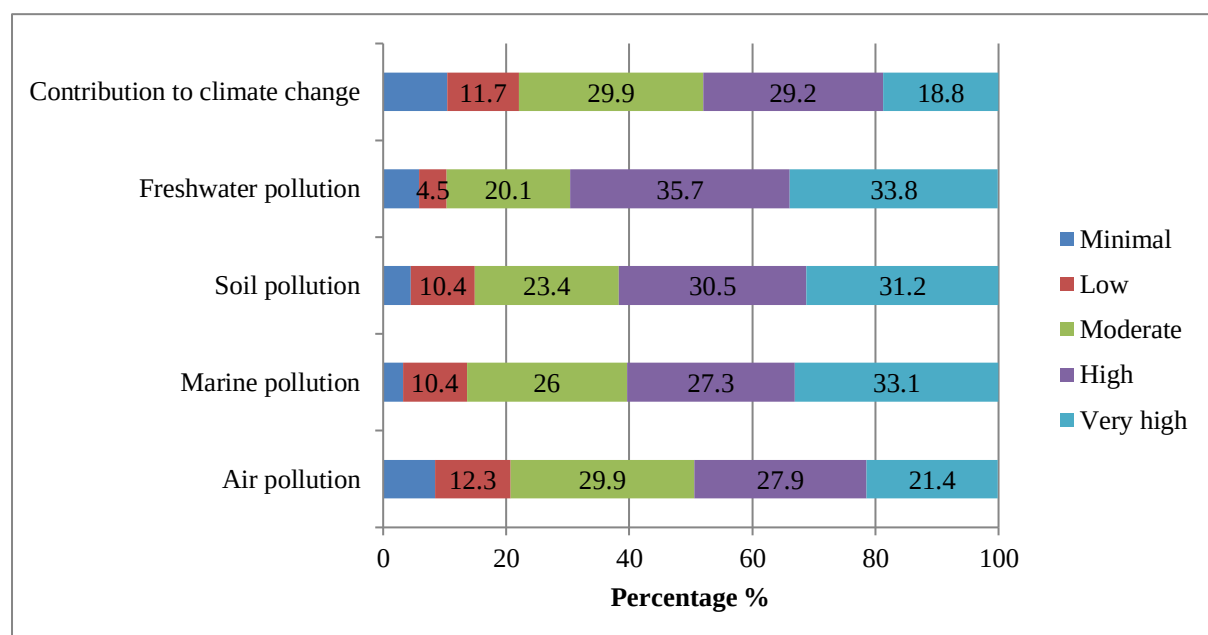


Figure 5: Microplastic environmental impact

A majority affirms that microplastics are being ingested by way of food and water whose quality has been tainted (68.9% combined agrees or strongly agrees) and are causing health issues such as respiratory problems reproductive disorders, and even cancers (70.8% combined views). All odds are set in favor of other dangers; inhalation as a mode of entry divides House opinion now sitting at 59.1% agreement with a significant 33.7%, neither for nor against.

There is a relatively high agreement regarding microplastics accumulation within organ and tissue (63.7%) and causing digestive problems (64.3%). However, a significantly high proportion remains neutral concerning these two aspects. While quite a number, a high percentage believes (51.3%) that potential health risks are well understood, an even greater majority (65.6%) strongly believes further inquiry is needed. Apparently, it signals that most of the populations are not only outspokenly concerned about health risks posed by microplastics but also that they see a present scientific uncertainty and calling for further research in the field. Health-wise, the issue of microplastics has been borrowed from the ground in much serious health percentage incidence among female respondents. Most of the respondents (70.8%) reported microplastics as related to respiratory problems, reproductive disorders, and even cancers, while 33.7% did not have any opinion about inhalation serving as an exposure.

This indeed justifies on-the-ground research into toxicological behavior of microplastics, translated into health impacts on humanity. The report dealt not only with the necessity of future research on toxicity impacts of microplastics on human health, but also on the imperative of science communication to the young public regarding such effects. Interestingly, 65.6% of responders felt that further research is necessary to determine possible health effects associated with microplastics, indicating an interest in ascertaining any hazards arising from possible exposure. Hence, this creates a strong possibility for universities and research organizations to field students as they advance in microplastics research projects in an environment where environmental stewardship is now being embraced. The reliability analysis (Cronbach's Alpha = 0.938) confirms that the 5 point ordinal Likert-scale responses are consistent and valid for among survey items, reinforcing the credibility of the findings. The results highlight significant public concern about microplastic health risks, emphasizing the need for further research and science communication.

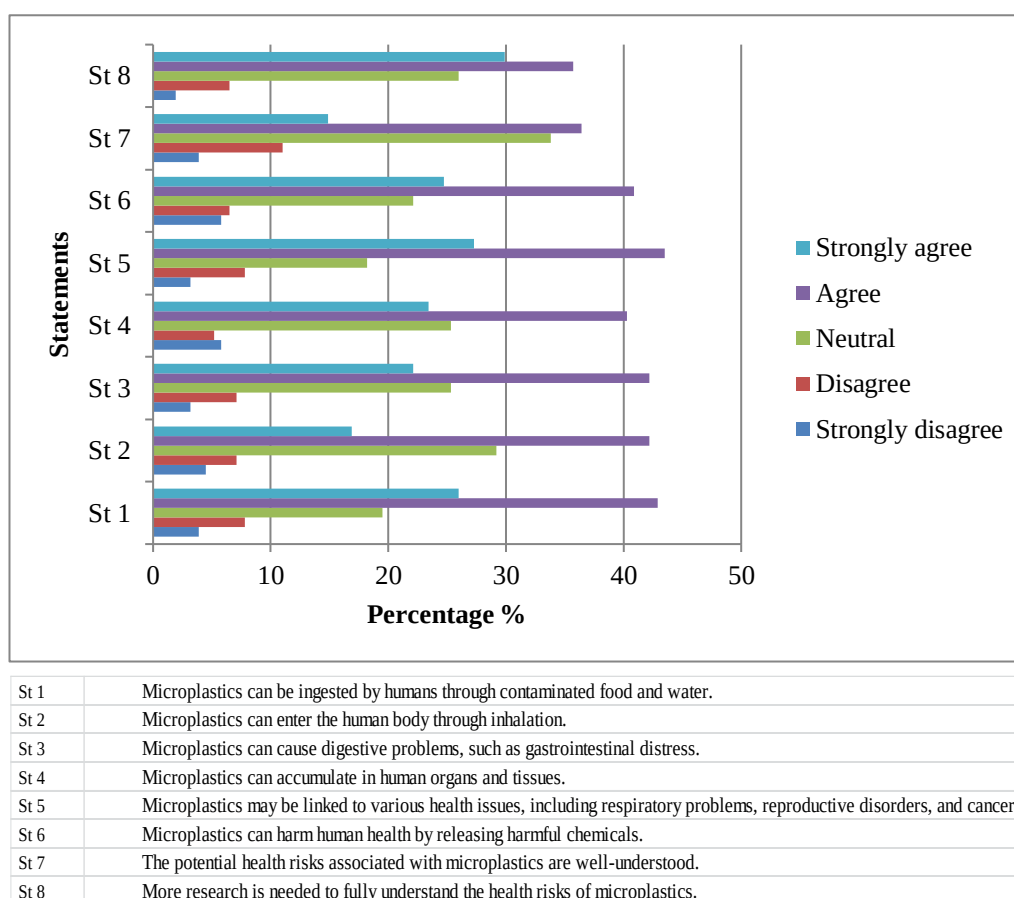


Figure 6: Agreements with statements about microplastic health risk

According to the undergraduates' personal experience in health issues related to microplastic, a majority of respondents (54.5%) report not experiencing any health issues they believe are related to microplastics. A notable proportion (14.3%) express concern about potential future risks despite not having experienced related health problems. Strangely enough, a similar percentage (13%) are unsure whether their health issues are caused by microplastics, which shows a sense of vacillation and possible apprehension. A smattering (9.7%) have health problems associated with some form of exposure to microplastics, whereas among them who suffer health problems, a smaller-sized group (8.4%) is experiencing complications yet remains unsure of the connection.

Generally, however, it would seem from the study that there is quite a lot of awareness, but there were gaps in knowledge concerning sources, exposure pathways, and health impacts. Therefore, there is a need for further education initiatives. Incorporating microplastic pollution in universities, advocating for research-based learning and using digital platforms to disseminate accurate information could increase the students' capability of mitigating the research gap concerning microplastic pollution.

4. Conclusion

The findings from the study revealed that under graduates of the Sabaragamuwa University have a relatively high level of awareness regarding microplastics. However, there is substantial missing knowledge on sources of microplastics, their environmental consequences, and the health risks associated with their presence. While industrial wastewater stands out as one major source (72.7%), the equally important ones of tire abrasion and synthetic textiles often went unnoticed. Whereas impacts on freshwater, soil, and marine ecosystem environments were acknowledged, low awareness existed with respect to air pollution and climate change by microplastics.

As for health risks, most agreed that microplastics could potentially enter the body via food and water, giving rise to serious health woes, such as threats to breathing and even cancer. The fact that 65.6% of respondents felt more research was needed suggests just how pressing a concern this is becoming and somewhat acknowledged the uncertainties still present in the research.

Acknowledgements

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ICSD 171

EXTRACTION OF CHITOSAN FROM SHRIMP EXOSKELETON AND DEVELOPMENT OF ECO-FRIENDLY BIOPLASTICS: A SUSTAINABLE WASTE- TO-RESOURCE APPROACH

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Abstract: Increased environmental considerations make the processing of bio waste valuable for advancing eco-friendly bioplastic trade. The Study aimed to focus on Extraction of chitosan from shrimp exoskeleton and subsequent development and evaluation of bioplastic films. Chitin was isolated through sequential chemical treatments involving with deproteinization, demineralization and Chitosan was isolated from deacetylation process. Bioplastics were produced through different ratios (1:1, 1:2, 1:3) of chitosan powder and Agar -Agar blending while preparing individual films from pure Agar -Agar and pure chitosan. FTIR analysis also done to point out the chitosan from the bioplastic films. From these investigations obtained 10.3% of chitin yield and 91g of chitosan. Characterization of bioplastic formulations determined how Shrimp shells to Agar ratios affected physical performance through series of tests like mechanical, thermal, water absorption and biodegradability properties. The analysis using Tukey's HSD test showed Agar -Agar formulation performed worse in folding endurance tests against all other factual combinations ($p < 0.05$) and Shrimp shell chitosan+ Agar (1:2) achieved higher endurance. The bioplastics gained increased tensile strength from the incorporation of Agar yet the 1:2 combination demonstrated the superior average strength value of 3.15 Mpa, since it creates an ideal combination for mechanical property advancement. Shrimp shell chitosan bioplastics maintained the best thermal properties because their melting point reached 257 °C due to the dense chitin and chitosan structure. Agar -based bioplastics show excellent moisture retention properties which makes them appropriate for applications that need water absorption capacity. The biodegradability changes of bioplastic formulations during time were analysed through a Repeated Measures ANOVA method and it heavily influenced by time on day 14 weight loss statistics show both linear trends and non-linear trends due to time which significantly influenced weight loss ($p = 0.000$). All the investigation demonstrates that biowaste produced chitosan bioplastics represent a sustainable alternative for packaging solutions and supplementary applications

Keywords: Bioplastics; Biodegradability; Chitin; Chitosan; Exoskeleton.

1. Introduction

The increasing severity of plastic pollution in the environment has triggered immediate demands to develop sustainable alternatives to petrochemical-based plastics which will also assist in reducing waste accumulation in landfills and oceans (Jain & Tiwari 2015; Singh et al. 2024; Tennakoon et al. 2023). The production of biodegradable bioplastics from biowastes demonstrates a great potential as a sustainable solution (Abu-Thabit et al., 2021; Li et al., 2024). Because they contain chitosan, alongside proteins as well as minerals and lipids (Fernandez & Ingber, 2014; Suryawanshi & Eswari, 2021).

The seafood industry produces shrimp shells through its manufacturing operations but usually throws these remains away or applies them only to low-value functions. Flexible plastic manufacturing employing shrimp shells reveals their hidden value because chitosan biopolymer exists as a natural substance with high potential for natural plastic production (Hudson et al., 2015). From the recent studies revealed that, chitin represents 30% to 40% of the dry weight of shells in shrimps. The extracted chitin can be converted into biodegradable chitosan demonstrates an output of 60% to 85% (Parthiban et al., 2017; Tokatlı & Demirdöven, 2017). This chitosan widely used for making bioplastics.

The production of bioplastics from shrimp shells delivers multiple benefits to the environment while developing domestic economic systems that advance green technology innovation. An increasing global seafood market creates increasing available shrimp shell resources for bioplastic manufacturing which opens new possibilities in sustainability through production and other single-use solution development while boosting economic value in seafood production regions and advancing sustainable manufacturing practices (Abina et al., 2023; Cooney et al., 2023).

Therefore, the aim of this study involves extracting chitin and chitosan from a widely available Shrimps species exoskeleton (*Penaeus monodon*) and using it to synthesize bioplastics through the combination of Agar -Agar at diverse proportions. This paper analyses the important characteristics of different formulations of bioplastic films while assessing mechanical properties and water uptake and thermal properties along with natural deterioration through soil burial, which previous research has not thoroughly investigated. This paper delivers ultimate remarks about potential future uses of Shrimp shell-derived bioplastics as well as enhancement opportunities for these technologies.

2. Methodology

2.1 Preparation of chitin powder

1 kg of *Penaeus monodon* shells (exoskeleton) were used to extract chitin through a series of chemical procedures. An initial stage involved washing the shells with tap water to remove exterior contaminants from their surface and dried thoroughly. The shell samples underwent a deproteinization step that used 1.0 M NaOH for 1-2 hours at room temperature followed by complete distilled water rinsing. Demineralization treatment involved submerging the material in HCl solutions between 1.0 M for 6 hours to remove calcium carbonate along with additional minerals. A secondary alkaline treatment consisted of exposing materials to 3–5% (w/v) NaOH at 60 °C for 6 hours to eliminate proteins and lipids that remained after processing. The material was washed upon reaching neutral pH followed by 18-hour drying at 50-60 °C. After that grinding of this dried samples for making chitin powder and weighted the yield by using digital scale (Cadano et al., 2020; Tokatlı & Demirdöven, 2017). Finally yield was calculated as shown in Eq. (1) below:

$$\text{Chitin Yield (\%)} = \left(\frac{\text{Weight of dried chitin}}{\text{Initial dry weight of shells}} \right) \times 100 \quad (1)$$

2.2 Preparation of chitosan from chitin (Deacetylation)

The solution of sodium hydroxide at 40-50% concentration was prepared by dissolving sodium hydroxide into distilled water. The deacetylation extent depends on the NaOH solution concentration adjustment. The NaOH solution receives a ratio addition of chitin at 1:10. A continuous stir will ensure even reaction conditions during this thermal process with a temperature range between 90-100°C for a time duration of 1–6 hours. The acetyl groups present on chitin molecules begin to degenerate into

chitosan during the reaction time. The mixture requires cooling before the solution gets neutralized with diluted hydrochloric acid (HCl). Distilled water washing the chitosan product removes all traces of NaOH solution and acid. Finally, the solution was dried inside an oven operating at 50-60°C until the sample reaches a constant weight (Puvvada et al., 2012).

2.3 Preparation of Bioplastic films

A mixture of Agar -Agar with chitosan powder at ratios between 1:1 to 1:3 and separate combinations of pure Agar -Agar and pure chitosan with gelatine aided to produce the bioplastics films. The preparation of the 1:1 ratio involved dissolving 10g of chitosan together with 10g of Agar -Agar in 150 mL of distilled water while maintaining temperatures between 70-80° C along with continuous stirring until the mixture became uniform and 1 ml of glycerol was added as plastizer. finally, this mixture was poured in to mould as a thin layer and the drying step which occurred inside an oven heated to 50-60°C. The same experimental procedure was used for both the 1:2 and 1:3 ratios where 20g and 30g of Agar -Agar were employed respectively. To prepare 10g pure Agar -Agar dissolved in 150mL water with 1 ml of glycerol before pouring and drying the mixture in a mould. To prepare 10g of pure chitosan film dissolved in 150mL water combined with 2g gelatine and glycerol followed the identical processing procedure.

2.4 Testing of Bioplastics

Folding Endurance Test: Bioplastics were tested for their folding endurance to determine their flexibility and durability (Chauhan et al., 2018). Each formulation produced uniform bio-plastic strips which measured 2 cm × 10 cm. Each strip obtained a midpoint mark for manual folding from the specified position until it presented visible breakage or cracking. The experiment ran until the plastic failed to support further folding while counting the total number of cycles until it broke. The testing procedure included five repeat tests of each formulation enabling reliable results while determining an average fold count. The test measured bio-plastic's bending resistance under repeated bending scenarios suitable for packaging applications and flexible material production.

The bio-plastic tensile strength assessment utilized manual weight-based testing methods. Each bio-plastic strip (2 cm × 10 cm) was measured for width and thickness to calculating its cross-sectional area values. The experimental setup included two components: a fixed support used for clamping one strip end while weights were suspended from the second end. The addition of weights started from minimal levels before the sample reached its breaking point. At last, the tensile strength was calculated as shown in Eq. (2) below

$$\text{Tensile Strength (MPa)} = \frac{\text{Force at Breaking (N)}}{\text{Cross-Sectional Area (m}^2\text{)}} \quad (2)$$

Thermal Stability (Melting Point): Assessment of bio-plastic thermal stability through the heating process of small material samples (Kim et al., 2005). A regulated heat system (Hot plate) heated the sample while starting the temperature at 50°C before a progressive increase occurred. The testing process involved recording both the softening point when the material softened and the melting point at which the bio-plastic lost its structure. Observations on bio-plastic behaviour like softening together with warping and bubbling were recorded while using a digital thermometer to track temperature changes. Five reliable results were obtained through repeated tests. The thermal stability measurements of bio-plastic determined its suitability in heat-exposed applications.

Water Absorption Test: Bio-plastic film water absorption ability was assessed through water immersion tests of 24 hours in distilled water (Wang et al. 2020) . Took measurements of the initial dry weight from all provided samples and determined water absorption percentage by measuring dry weights before and after soaking followed by this calculation as shown in Eq. (3) below

$$\text{Water Absorption (\%)} = \left(\frac{\text{Wet Weight} - \text{Dry Weight}}{\text{Dry Weight}} \right) \times 100 \quad (3)$$

Five identical tests of each formulation determined both the water affinity and moisture retention power of the bio-plastic.

Biodegradability Tendency Analysis: Analysis biodegradability using small bio-plastic samples that underwent burial in soil (Slezak et al., 2023). The test samples were removed at set periods beginning on Day 0 and progressing through Day 7 and Day 14 to measure remaining weight. The weight loss percentage was calculated through the implementation of this formula as shown in Eq. (4) below.

$$\text{Weight Loss (\%)} = \left(\frac{\text{Initial Weight} - \text{Remaining Weight}}{\text{Initial Weight}} \right) \times 100 \quad (4)$$

The analysis delivered important knowledge regarding the environmental friendliness of bioplastics while revealing their sustainability potential.

2.5 Statistical Analysis

The SPSS version 26.0 was used to analyse all the data. The results will be presented as means + standard deviation (SD). Each formulation was tested on five different repetitions (n = 5) in case of mechanical and thermal properties and water absorption properties. The experiment of biodegradability was conducted as triplicates (n = 3).

One-Way Analysis of Variance (ANOVA) was done on all the analyses to establish the significance between the differences in the treatments with the significance level of alpha =0.05. Where ANOVA showed a substantial difference, Tukey Honestly Significant Difference (HSD) post hoc was used to determine pair wise differences.

The repeated measure ANOVA was used across time (0, 7, 14 days) on biodegradation. Linear and quadratic polynomial contrasts were used to investigate trends of degrading. All data were checked with assumption of normality (Shapiro-Wilk test) and homogeneity of variance (Levene)s test.

3 Results and Discussion

3.1 Chitosan Yield Percentage from shrimp shells

The investigation obtained approximately 103 g of purified chitin after working with 1 kg of shrimp shells which resulted in a final chitin yield of 10.3%. The obtained yield contests previous findings regarding shrimp shells yield ranges at 15-30% especially when considering their species type along with extraction and shell composition factors (Bahasan et al., 2016; Mahboob, 2014; Parthiban et al., 2017)). From the deacetylation of chitin gave chitosan approximately 91g.

The moderate yield from this study can be explained as a polymer compound chitin consists of elements that contain N-acetylglucosamine units. The deacetylation reaction eliminates the –COCH₃ groups from the acetyl units which transforms many units into glucosamine. The chemical modification results in reduced molecular weight (Kadouche et al., 2016; Rashid et al., 2012).Some practical applications may reduce the weight like higher deacetylation or reaction conditions like temperature, concentration of chemicals, time etc. (Kadouche et al., 2016; Rashid et al., 2012).However the findings showed waste shrimp shells provides a sustainable opportunity for obtaining chitosan which leads to a dual benefit of environmental protection and green material development through aquaculture by products.

3.2 FTIR Spectrum of chitosan film bioplastics

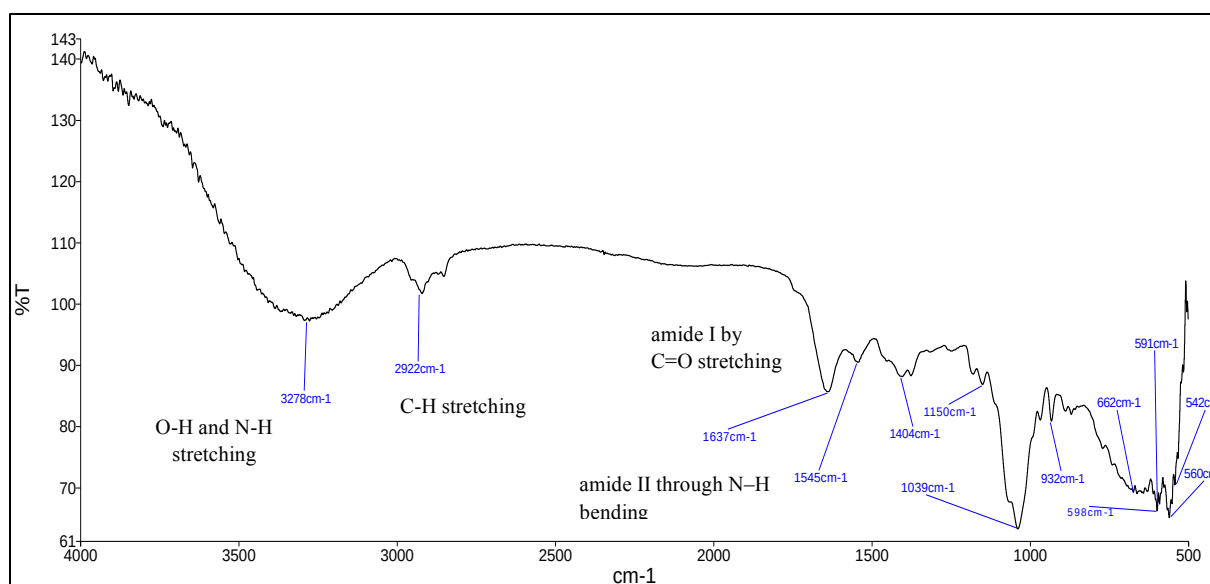


Figure 1: FTIR Spectrum of bioplastic film extracted from chitosan films

Analysis of FTIR spectrum from Figure 1 confirms strong indications of chitosan biopolymer existence within shrimp shell-derived bioplastics because it comes from chitosan deacetylation. The wide absorption band located at 3278 cm⁻¹ results from hydroxyl (O–H) stretch combinations with amino (N–H) stretching vibrations that occur in the chitosan molecular structure. The stretching vibrations of aliphatic chains present in polysaccharides that include chitosan appear as a peak at 2922 cm⁻¹. The Amide I band at 1637 cm⁻¹ and Amide II band at 1545 cm⁻¹ arise from C=O stretching vibrations of residual acetyl groups and N–H bending vibrations respectively to verify the chitosan production. The CH₂ bending vibrations appear in the range of 1420–1450 cm⁻¹ and the C–H bending vibrations occur at 1404 cm⁻¹ to show consistency with a polysaccharide backbone. A peak at 1150 cm⁻¹ in the spectrum shows C–O–C asymmetric stretching and identifies the glycosidic bonds that exist in chitosan framework. The strong C–O stretching vibrations between 1030–1070 cm⁻¹ match chitosan structural bonds as do the characteristic β-glycosidic linkages at 895 cm⁻¹.

3.3 Characterization of Bioplastic from different formulations

An assessment of bio-plastic formulations (mixture of Agar -Agar with chitosan powder at ratios between 1:1 to 1:3 biofilms and separate combinations of pure Agar -Agar and pure chitosan with gelatine films) determined how Shrimp shell-to-Agar ratios affected physical performance through tests for mechanical, thermal and water absorption and biodegradability properties. Each bio-plastic formulation showed different results in their ability to sustain folds and withstand heat while absorbing water and undergoing degradation.

3.3.1 Folding Endurance Test

Bio-plastic formulations demonstrated significant distinct folding performance in the folding endurance test ($F(4,20) = 173.091$, $p = 0.000$, one - way ANOVA; $n=5$ per group). Agar -Agar showed poor folding endurance because its 22.40 ± 2.32 folds suggest that it behaves as a brittle nature with weak mechanical capabilities. The Shrimp shell chitosan strain reached 43.60 ± 3.64 folds yet combinations of Shrimp shell chitosan with Agar produced steadily better folding endurance until Shrimp shell chitosan+ Agar (1:2) delivered the highest value at 72.20 ± 2.68 folds. The analysis using Tukey's HSD test showed Agar -Agar formulation performed worse in folding endurance tests against all other material

combinations ($p < 0.05$) and Shrimp shell chitosan + Agar (1:2) achieved higher endurance than all combinations ($p < 0.05$).

The addition of Agar to Shrimp shell-based bioplastics produces increased mechanical properties through the structural strengthening and flexible characteristics obtained from Agar incorporation. The observed improvement in folding endurance results from the balanced behavioural relationship that occurs between chitosan in Shrimp shells and Agar's hydrophilic matrix structure. The recorded findings closely matched with other research findings that has demonstrated polysaccharides including Agar strengthen bioplastic structures by improving protein-based material compatibility (Boey et al., 2022; Guo et al., 2021).

3.3.2 Tensile Strength Test

Table1:average tensile strength of bioplastic films in Mpa

Sample types	Average Tensile Strength(Mpa) $\pm$ standard deviation
Shrimp shell chitosan film	1.90 $\pm$ 0.15
Shrimp shell chitosan: Agar-Agar (1:1)	2.16 $\pm$ 0.10
Shrimp shell chitosan: Agar-Agar (1:2)	3.15 $\pm$ 0.13
Shrimp shell chitosan: Agar-Agar (1:3)	2.35 $\pm$ 0.17
Pure Agar - Agar	1.22 $\pm$ 0.16

According to the Table 1 revealed, all bioplastic proportions demonstrated different tensile strength measurements. The average tensile strength of chitosan obtained from Shrimp shell chitosan films amounted to 1.90 MPa. The bioplastics gained increased tensile strength from the incorporation of Agar yet the 1:2 combination demonstrated the superior average strength value of 3.15 MPa, because it creates an ideal combination for mechanical property advancement. The physical structure became weakened by too much Agar which caused the tensile strength to decrease in 1:3 proportion. The 1:2 proportion between Shrimp shell chitosan and Agar lead to maximum tensile strength at 3.15 MPa the tensile strength of Agar came out at 1.22 MPa because Agar exists as a brittle material when used singly. These results authorise that Agar lacks the structural stabilization which Shrimp shells contribute to materials thus composites become necessary to reach desired mechanical specifications. These finding also validated by Ali & Andriyana, (2020) and Hu et al. (2016).

3.3.3 Thermal Stability Test

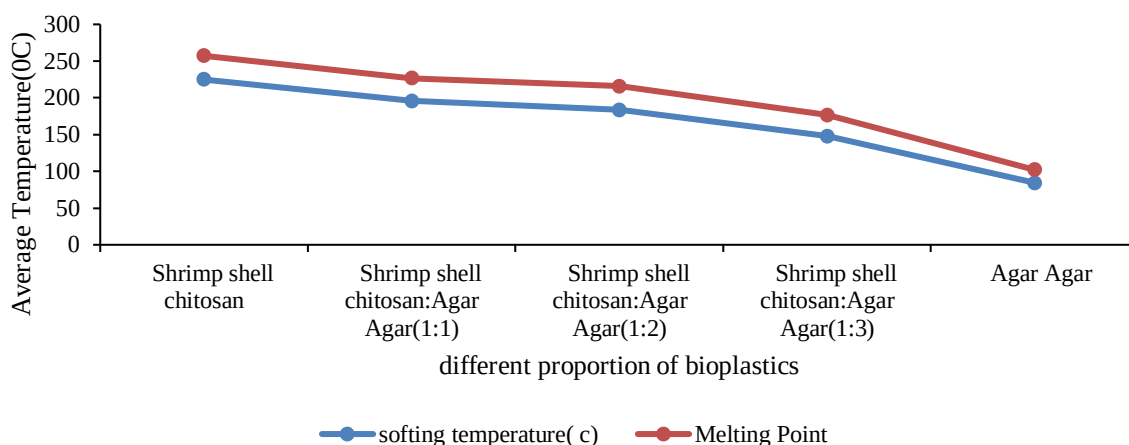


Figure 2: The thermal stability analysis of Bioplastic films across all formulations of bioplastics

The Figure 2 illustrates the thermal stability results and revealed significant discrepancies between different formulations ($p = 0.000$, one-way ANOVA, $n=5$). The Agar-Agar bioplastic films exhibited significantly reduced thermal stability compared to all other test formulations while Shrimp shell chitosan films displayed maximum thermal degradation resistance based on results from Post-hoc Tukey's test ($p < 0.05$). Shrimp shell chitosan bioplastics maintained the best thermal properties because their melting point reached 257°C due to the dense chitin and chitosan structure seen in Shrimp shells being notoriously resistant to heat degradation. Agar-Agar revealed weak thermal characteristics as it melted at 101°C . The addition of Agar to Shrimp shells through the Shrimp shell chitosan+ Agar (1:2) composition helped maintain thermal properties up to notable levels while achieving a softening temperature of 183°C and a melting point of 216°C . Thermal stability diminished when using the Shrimp shell chitosan+ Agar (1:3) ratio since the material gained more water content and formed a less dense composite structure.

As Agar possesses high water affinity properties the amount of water retained within the bioplastic structure increases when Agar concentration increases (Belay et al., 2017). High moisture content caused by the formulation creates conditions that promote rapid thermal degradation through the reduction of heat resistance. High Agar levels create dilution effects that reduce the amount of thermally stable ingredients from Shrimp shells while producing a weak and less dense polymer structure.

3.3.4 Water Absorption Test

Statistical difference as shown by one-way ANOVA ($n=5$) indicated that there was all statistically significant difference ($p < 0.05$) of water absorption among all treatments. There were differences that were significant among every pair ($p < 0.05$) using post hoc tests. The experimental results from Figure 3 indicated that water absorption capacity strongly depends on the proportion of Shrimp shell chitosan to Agar used in the bioplastics. Agar-Agar when used as a pure substance absorbed 100% water due to its natural affinity for hydrophilic molecules. The Shrimp shell chitosan + Agar formula with a ratio of 1:3 absorbed 77.36% water according to the test results. The water absorption degree of pure Shrimp shell chitosan bioplastic ranked the lowest at 41.18% because chitosan which composes Shrimp shells shows natural resistance to water absorption. The water absorption values of the 1:2 (68.65%) and 1:1 (57.71%) Shrimp shell chitosan to Agar formulations fall between high and low levels due to the way hydrophilic and hydrophobic components interact with moisture. Agar-based bioplastics show excellent moisture retention properties which makes them appropriate for applications that need water absorption capacity.

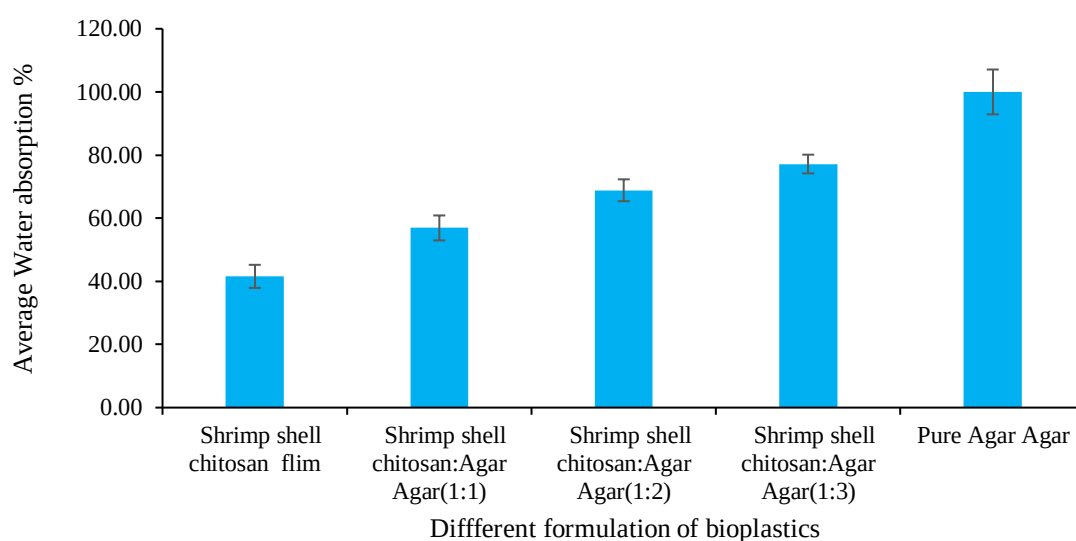


Figure 3: Water Absorption assessment of Shrimp shell chitosan - Agar based Bioplastic films

A lower absorption of shrimp shell chitosan (41.18%) than horse mackerel chitosan was observed, since it is semi-hydrophobic, an observation by Zheng et al. (2003). In our study, we also find that, like Barikani et al. (2014), the chitosan-alginate composites had an intermediate absorption of water depending on the ratios of the blends. The 1:2 ratio of Shrimp shell to Agar demonstrates beneficial properties which combine effective water retention characteristics with mechanical stability making it an ideal candidate for biodegradable materials that need to interact moderately with moisture without structure degradation

3.3.5 Biodegradability Analysis

Table 2: Biodegradation of different formulations of bioplastics over 14 days under Soil Burial test

Average of Biodegradation weight loss percentage			
Different formulation of bioplastics	0 days	After 7 days	After 14 days
Shrimp shell chitosan film	0	8.33	18.33
Shrimp shell chitosan: Agar-Agar (1:1)	0	14.33	27
Shrimp shell chitosan: Agar-Agar (1:2)	0	19.33	29.33
Shrimp shell chitosan: Agar-Agar (1:3)	0	30.67	40.67
Pure Agar-Agar	0	45.67	58

Bio-plastic formulations underwent biodegradability assessments while placed under the soil up to fourteen days. The test period revealed that Agar-Agar films experienced the most extensive biodegradation reaching 58% weight loss during 14 days. The Shrimp shell chitosan films exhibited limited biodegradation since they lost their weight by 18.33% during the 14-day period. Biodegradation occurred faster in Shrimp shell chitosan-based formulations containing Agar as the 1:2 Shrimp shell-to-Agar ratio achieved 29.33% weight loss by Day 14. The 1:1 and 1:3 combinations reached biodegradation levels of 27% and 40% respectively (*see* Table 2).

The biodegradability changes of bio-plastic formulations during time were analysed through a Repeated Measures ANOVA (n=3) method. Biodegradation processes of bioplastic formulations are heavily influenced by time according to the research findings. On day 14 weight loss statistics show both linear trends and non-linear trends due to time which significantly influenced weight loss and initial weight and final weight measurements ($p = 0.000$). The linear contrast shows how bioplastic weights decrease uniformly but the quadratic contrast demonstrates that biodegradation speeds up or slows down at specific timepoints indicating multiple biodegradation patterns occur.

Research shows Agar works as a polysaccharide that speeds up decomposition once used as an ingredient in Shrimp shell-bioplastics. The fastest degraded (58 % in 14 days) were pure agar films in line with a study by Altaf et al. (2022) with over 50 percent degradation of films in comparable conditions. Conversely, chitosan isolated in shrimp shells decomposed at a lower rate (18.33%), which is equivalent to the microbial recalcitrance reported in Yanat & Schroën (2023) since chitosan has the semi-crystalline structure. When Agar is combined with Shrimp shell the degradation process accelerates thus improving the materials fitness for environmentally friendly usages (Altaf et al., 2022; Barikani et al., 2014; Yanat & Schroën, 2023)

3.4 Limitation of the Study

To begin with, the quality of chitosan extraction and hence bioplastics could be variable because of the existing natural variation in the composition of the shell of shrimp (e.g., chitin content). Reproducibility can be enhanced on future studies with standardized raw material acquisition, with a compositional analysis. Secondly, although the extraction and film making process was very successful at the lab scale, it could have significant issues when used in the industrial scale in terms of cost, equipment, and waste problem. It is proposed to run pilot-size production tests and cost-effectiveness analysis to deal with the problem of scalability.

Finally, the test of the biodegradability only occurred in short-term conditions of the soil. Further long-term tests under different environmental conditions (e.g., marine, compost), are required to classify fully long-term degradation behaviour. To proceed with future studies, it would be advisable to integrate modern methods of analysis (e.g., FTIR, SEM) in order to gain a better insight in the structural and functional characteristics of the produced bioplastics

3.5 Potential applications and limitations of the developed bioplastics in real-world scenarios.

The bioplastics obtained by using chitosan derived shrimp shell and Agar-Agar have got promising attributes that indicate a variety of practical uses in a real-life situation. They can be used as sustainable packaging material because of their high tensile strength, impartial thermal stability and biodegradability, especially in dry and semi-moist foodstuffs (Ali & Andriyana, 2020). The most notable one, 1:2 chitosan: Agar formulation, possesses mechanical and moisture properties suitable to immediate packaging requirements, which in essence, provide a feasible replacement of petroleum-based plastic in the long perspective. These bioplastics could be used in the agricultural sector as biodegradable mulch films or as seed trays where they will cover the soil without any toxic compounds remaining after degradation (Hu et al., 2016). They can also be applied in the biomedical and pharmaceutical field, as the dressing to treat a wound or even a drug delivery method, as made relevant by Altaf et al. (2022) and Barikani et al. (2014). Moreover, these materials can be tested on the existing single-use product: disposable cutlery, plates, and carry bags, which are in increasing demand because of the awareness of the necessity of biodegradability of consumer products.

Nevertheless, some of their drawbacks might make them not to be used immediately within the commercial and industrial sectors. Moisture sensitivity is one of the major limitations; despite the chitosan act as a source of hydrophobicity, interaction with agar makes the films more prone to moisture and thereby not effective in high humidity or high-water content products packaging (Zheng et al., 2003). The other constraint is their susceptibility to mechanical damages. Such bioplastics are also relatively weak on tensile strength and cannot therefore be used in load bearing or high stress cases, as compared with conventional plastics (Belay et al., 2017). In addition, they have the decreased shelf-life because they can be microbially degraded and encounter shifting physical conditions because of variances in storage conditions.

In order to address such drawbacks, the future investigation ought to be carried to the betterment of water resistance by employing naturally incorporated coating or cross-linking procedures (Guo et al., 2021) and mechanical strength by the use of bio-fillers or nanomaterial. The assessment of the practicality of the materials also should be done with the help of comprehensive life cycle assessments and field trials in various conditions of the environment. In addition, a combination with industry actors and favourable policy frameworks might help to shift these bioplastics out of the lab to become viable green alternatives.

4. Conclusion

The research demonstrates that Agar addition to bioplastics from Shrimp shells (chitosan) strengthens their mechanical properties while improving thermal stability alongside water absorption and biodegradability performance. The research indicates that Shrimp shell-to-Agar ratios of 1:2 combine optimal strength with flexibility and biodegradability properties suitable for multiple bioplastics uses. Tests under real life conditions and additional composition improvements will help develop strong durable sustainable bioplastics that can function in environmental applications.

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UNIVERSITY-INDUSTRY PARTNERSHIPS FOR SUSTAINABLE DEVELOPMENT

ICSD 064

**ASSESSING TECHNICAL EFFICIENCY OF PUBLIC SCHOOLS IN SRI
JAYAWARDENAPURA EDUCATION ZONE THROUGH DATA
ENVELOPMENT ANALYSIS****M. A. C. Hansamali*, N. Kurukulasooriya***University of Ruhuna, Wellamadama, Mathara.***Correspondence Email: chalani.17237@uhss.ruh.ac.lk, TP: +94768515025*

Abstract: The free education system of Sri Lanka provides an equal opening for every child to receive the school education. However, research on secondary public education system in Sri Lanka discusses poor exam performances compared to the available resources to school and thereby significant disparities between school resources and educational outcomes. Consequently, current study evaluates the technical efficiency of Type-2 schools in the Sri Jayawardhanapura Education Zone (JEZ) and determines whether there are significant deviations in technical efficiency between schools with equal to or less than 250 students and those with more than 250 students. Literature defines technical efficiency of a school as the ratio of the school's actual educational outcome to the optimal level of the educational outcome at a given level of resources. Nonparametric Data Envelopment Analysis (DEA) and Tobit regression were employed for the data analysis endeavor. This study depends on secondary and data and are collected from the JEZ. Student-teacher ratio, student-graduate teacher ratio, and student-classroom ratio were used as input variables, while the Grade 5 scholarship examination results and G.C.E. Ordinary Level results were the output variables in DEA. The number of computers, extra reading books provided by school libraries, and sanitary facilities were efficient determinants. Findings revealed that Type-2 schools in JEZ were technically efficient and student-teacher ratio, student-classroom ratio, student-graduate teacher ratio, availability of extra reading books, and sanitary facilities are the significant determinants of technical efficiency. Therefore, policy makers need their attention to improve the technical efficiency of public schools focusing on the significant factors identified.

Keywords: Data envelopment analysis, Public schools, Jayawardenapura education zone, Technical efficiency, Tobit regression

1. Introduction

1.1 Background of the Study

Education is an investment and providing education is an essential responsibility of the government of country (Pigou, 1920). Children who receive primary socialization through the family undergo secondary socialization through school (Jones, 2005). In Sri Lanka, there are ninety-nine education zones, including the Sri Jayawardhanapura Education Zone (JEZ), which is located in the Colombo district and consists of 88 schools (Ministry of Education, 2021). According to the education structure of Sri Lanka, schools are divided into five types: National schools, 1AB, 1C, Type-2, and Type-3 (Dorabawila et al., 2002). JEZ consists of 9 National schools, 21 1AB schools, 15 1C schools, 25 Type-2 schools, and 27 Type-3 schools (Ministry of Education, 2021).

Teaching quality is the foundation of a successful educational process. Sri Lanka is renowned for offering free education in the post-independence era, ensuring that each child has an equal opportunity to receive education (Herath, 2008). However, resource allocation among public schools has not been uniform over the years in Sri Lanka (Abeysekara & Arunatilake, 2018). Sri Lanka has 10,155 government schools, with 1,439 schools having less than 50 students and only 32 schools having more than 4,000 students. Additionally, only 1,949 schools function with grade spans from 1 to 13 (Ministry of Education, 2021). Among the 88 public schools in JEZ, only 25 schools have more than 1,000 students.

Scholars have been addressed the efficiency issues in schools including public schools (Chakraborty, Biswas, & Lewis, 2001; Chakraborty, 2009). The performance of school system in Sri Lanka has also been addressed in literature (Ranaweera, 2003; Gunawardena, 2004; Athukorala, & Senaratne, 2012; Fernando, & Ranasinghe, 2015; Wickramasinghe, 2020). Most of the studies conducted so far at district level or provincial level, which mask intra-regional disparities. There is no zone-specific DEA study (e.g., Sri Jayawardanapura education zone), which is crucial for micro-level policy targeting. This study addresses the current research gap focusing the contributions including evaluating technical efficiency of public schools in the Sri Jayawardanapura education zone, used updated DEA techniques with contextual/environmental factors, include both quantitative and qualitative output measures, apply a second-stage analysis to explain inefficiencies and offer policy implications and simulations for better resource allocation.

Accordingly, the main objective of this study is to examine the technical efficiency of Type-2 schools in JEZ. Specifically, the study aims to determine the extent to which resources are maximized in these schools and to evaluate whether there is a significant deviation in technical efficiency between schools with equal to or more than 250 students and those with fewer than 250 students in Type-2 schools of JEZ.

1.2. Significance of the Study

As a developing country, Sri Lanka has limited resources. Identifying schools operating at optimal efficiency levels allows policymakers to allocate resources effectively, leading to better facilities, improved teacher-student ratios, and enhanced learning environments (Mayerle et al., 2022). Abeysekara and Arunatilake (2018) found that schools with better results tend to have experienced teachers and skilled principals. According to Herath (2008), following provincialization, the responsibility for maintaining all schools, except for 322 national schools, lies with Provincial Councils. These councils are responsible for recruiting teachers, conducting training programs, constructing facilities (such as school buildings, libraries, and playgrounds), and distributing teaching aids and furniture. Consequently, decisions made by Provincial Councils significantly affect student performance.

Since this study evaluates the technical efficiency of Type-2 schools in JEZ, which are maintained by the Provincial Council, the findings will help assess the productivity of resource allocation, the quality of educational outcomes, fairness in access to education, and necessary policy improvements. This will provide valuable insights for the Provincial Council in making informed decisions regarding these schools. Furthermore, this study serves as a pilot study for future research on the technical efficiency of Sri Lankan schools. Its findings will contribute to the development of a more effective and efficient education system, fostering Sri Lanka's growth and prosperity by producing educated and skilled citizens.

2. Literature Review

The existing literature has been examined to identify the variables of the study. The student-teacher ratio was the most common input variable used to measure technical efficiency (Chakraborty, 2009; Franta & Konency, 2009; Chakraborty *et al.*, 2001; Mizala *et al.*, 2002). Furthermore, school resources have a strong and positive influence on students' educational outcomes (Hill *et al.*, 2005; Rockoff, 2004; Card and Krueger, 1996). According to Hanushek (2003) demographic characteristics and family background affect the student's performance rather than other resources. Some scholars determined that in developing countries, there is a positive relationship between education expenditure, human resources, and performance (Pritchett & Filmer, 1999; Lockheed & Hanushek, 1988). Evaluating production or outcome in school is challenging (Herath, 2008). Most scholars have used standardized test scores of students as the output of the schools (Chakraborty, 2009; Chakraborty *et al.*, 2001; Jimenez & Sawada, 1999 and Card and Krueger, 1996). However, Mahumudi *et al.* (2014) used the dropout rate as the output. Additionally, academic performance in mathematics and academic performance in the sciences have been employed as outputs (Gimenez *et al.*, 2007). According to Batool & Chaudry (2019), the pass rate of students is an output that can measure the students' performance. In Sri Lankan context, Herath (2008), used G.C.E Ordinary Level (O/L) and Advanced Level (A/L) results as outputs when measuring the internal efficiency of education.

Upon reviewing various studies on technical efficiency of schools, Stochastic Frontier Analysis (SFA) and Data Envelopment Analysis (DEA) were used to measure technical efficiency (Anderson *et al.*, 2016; Franta & Konency, 2009; Chakraborty, 2009; Gimenez *et al.*, 2006; Mizala *et al.*, 2002 and Chakraborty *et al.*, 2001). The efficiency of a school means it uses minimum resources to produce a given level of educational outcome (Chakraborty, 2009 and Chakraborty *et al.*, 2001). DEA measures the distance of other schools from that frontier, revealing the most efficient schools. The most important advantage of DEA is it allows multiple inputs and multiple outputs (Halkiotis *et al.*, 2018; Balasooriya, 2004 and Chakraborty *et al.*, 2001) while providing individual efficiency scores for each school in the sample. It further facilitates identifying relatively efficient educational units, comparing to inefficient educational unit (Halkiotis *et al.*, 2018). DEA also enables to evaluate efficiency by measuring non-monetary factors including un-priced inputs such as decision-making, and examination results, (Balasooriya, 2004). The DEA results only give the efficiency score while not proving what actions should be taken to increase the efficiency of schools which does not maximize the efficient score (Mahmudi *et al.*, 2014). The sensitivity in returns to scale in education production frontier generate technical problems of DEA (Balasooriya, 2004).

3. Methodology

3.1. Research Design

This empirical research work was entirely based on secondary data collected through the records of schools of JEZ. According to the objectives, all the Type 2 schools in JEZ used as the sampling units of this study. The quantitative research approach was used. Data were collected based on input variables, output variables, and efficiency determinants. Input variables were the student-teacher ratio, student-graduate teacher ratio, and student-classroom ratio. Efficiency determinants were the number of computers, number of extra reading books provided by school library, and the sanitary facilities

(number of toilets). The percentage of students who passed the grade 5 scholarship exam and the percentage of students who passed the G.C.E. Ordinary level exam were the output variables.

3.2 Theoretical Framework

3.2.1. Concept of Technical Efficiency

The technical efficiency is the ratio of the producer's actual (observed) production, and the optimal level of production can be produced with given inputs and the present state of technology (Franta & Konency, 2009 and Mizala *et al.*, 2002). Under the assumption of fixed input, technical efficiency is the ratio between the observed output and the maximum output, and under the assumption of fixed output technical efficiency is the ratio between the observed input and the minimum input (Porcelli, 2009). Output-oriented and input-oriented approaches are the mostly used two approaches for measuring Technical Efficiency (Ramanathan, 2003). In the output-oriented approach, the concern is with how much that output can be increased at a given level of input. On the other hand, the input-oriented approach is concerned with using minimum inputs to achieve a given level of output (Zamorano, 2004).

3.2.2. Introduction to Data Envelopment Analysis

DEA was used to determine the technical efficiencies of Type-2 schools in JEZ. It was invented by Charnes, Cooper, and Rhodes in 1978 (Batool & Chaudry, 2019; Halkiotis *et al.*, 2018; Anderson, 2016; Gimenez *et al.*, 2007 and Ramanathan, 2003). It was developed under the assumption of constant returns to scale by applying a linear programming method for the efficiency measurement of non-profit organizational units which are termed decision-making units (DMU) (Ramanathan, 2003 and Batool & Chaudry, 2019). The DEA technique endeavors to find the efficiency of DMUs when producing output by using available resources (Charnes *et al.*, 1978).

3.2.3. Mathematical Formulation of DEA Model

“Let there be N DMUs whose efficiencies have to be compared. Let us take one of the DMUs, say the m^{th} DMU, and maximize its efficiency according to the formula given above. Here the m^{th} DMU is the reference DMU. The mathematical program now is,

$$\text{Max } E_m = \frac{\sum_{j=1}^J v_{jm} y_{jm}}{\sum_{i=1}^I u_{im} x_{im}} \quad (1)$$

Subjected to

$$0 \leq \frac{\sum_{j=1}^J v_{jm} y_{jn}}{\sum_{i=1}^I u_{im} x_{in}} \leq 1; \quad n = 1, 2, K, N \quad (2)$$

$$v_{jm}, u_{im} \geq 0; \quad i = 1, 2, K, I; \quad j = 1, 2, K, J$$

where E_m is the efficiency of the m^{th} DMU, y_{jm} is the j^{th} output of the m^{th} DMU, v_{jm} is the weight of that output, x_{im} is i^{th} input of the m^{th} DMU, u_{im} is the weight of that input, and y_{jn} and x_{in} are j^{th} output and i^{th} input, respectively, of the n^{th} DMU, $n = 1, 2, \dots, N$. Note that here n includes m ” (Ramanathan, 2003).

The set of formulas given in (1) and (2) leads to a nonlinear programming problem. Therefore, in 1978 Charnes, Cooper, and Rhodes (CCR) introduced the CCR model with a linear programming problem (Mizala *et al.*, 2002). CCR DEA model was introduced as input minimization and output maximization models. The general output maximization CCR DEA model is,

$$\text{Max } Z = \sum_{j=1}^J v_{jm} y_{jm} \quad (3)$$

Subject to

$$\sum_{i=1}^I u_{im} x_{im} = 1 \quad (4)$$

$$\sum_{j=1}^J v_{jm} y_{jn} - \sum_{i=1}^I u_{im} x_{in} \leq 0 \quad n = 1, 2, K, N \quad (5)$$

$v_{jm}, u_{jm} \geq \varepsilon; i = 1, 2, K, I; j = 1, 2, K, J$

Then the general input minimization CCR DEA model is,

$$\text{Min } z' = \sum_{i=1}^I u'_{im} x_{im} \quad (6)$$

Subject to

$$\sum_{j=1}^J v'_{jm} x_{jm} = 1 \quad (7)$$

$$\sum_{j=1}^J v'_{jm} y_{jn} - \sum_{i=1}^I u'_{im} x_{in} \leq 0 \quad n = 1, 2, K, N \quad (8)$$

$v'_{jm}, u'_{jm} \geq \varepsilon; i = 1, 2, K, I; j = 1, 2, K, J'$

(Ramanathan, 2003).

3.2.4. Tobit Regression Model

After measuring technical efficiencies using DEA, then the second stage identifies the variables that significantly impact the technical efficiency of schools, using Tobit regression model. The Tobit regression model was introduced by Tobin in 1958 and it is assumed that the dependent variable tends to concentrate its values around a limited value, usually zero (McDonald & Moffit, 2010).

A dependent variable that takes restricted values is a limited dependent variable (Fall, 2008). Since technical efficiencies took values between 0 and 1 (i.e. $0 \leq \text{value of efficiency} \leq 1$), technical efficiency is a limited dependent variable. The Tobit regression model can be expressed as follows,

$$y_t = x_t \beta + u_t \quad (9)$$

$$\text{If } x_t \beta + u_t > 0 \quad (10)$$

$$\text{If } x_t \beta + u_t \leq 0 \quad (11)$$

$t = 1, 2, \dots, N'$ (McDonald & Moffit, 2010).

3.2.5. Two-Sample T-test

Two-sample t-tests and paired sample t-tests can be identified as the two types of t-tests (Kim, 2015). In this study, a two-sample t-test was used to evaluate the mean difference in technical efficiency between schools that have equal or less than 250 and more than 250 students in Type 2 schools of SJZ. The two-sample t-test can be employed under the assumption that the population variances are equal or the population variances are not equal. Since the population variances were not known in this case, equal variances were not assumed. Therefore, the test statistic of the two-sample t-test was,

$$t = \frac{\bar{x}_1 - \bar{x}_2}{\sqrt{\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}}} \quad (12)$$

Where $df = \frac{\left[\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2} \right]^2}{\left[\left(\frac{1}{n_1 - 1} \right) \left(\frac{s_1^2}{n_1} \right)^2 + \left(\frac{1}{n_2 - 1} \right) \left(\frac{s_2^2}{n_2} \right)^2 \right]}$ and $\alpha = 0.05$ (Kim, 2015).

3.3. Research Tools

Microsoft Excel was used to organize and prepare the collected data for the required analysis according to the study's objectives. The Win4DEAP was used to implement the Data Envelopment Analysis to evaluate the technical efficiencies of the Type-2 schools in the SJZ. The two-sample t-test was used to evaluate the mean difference in technical efficiency between schools that have equal or less than 250 and more than 250 students in Type 2 schools of SJZ using Minitab software. Furthermore, the Gretl software was used to analyze the Tobit regression model.

4. Results and Discussion

4.1 Discussion of the Results of Technical Efficiency

Technical efficiency scores obtained from a two-stage DEA model under Variable Return to Scale (VRS) are presented in Table 1. Most of the schools are found to be efficient showing efficiency scores less than one. Rukmale Maha Vidyalaya, Thalahoma Maha Vidyalaya, Sri Dewamiththa Maha Vidyalaya, Munidasa Kumaratunga Vidyalaya, and Gamini Vidyalaya are fully efficient under input-oriented and output-oriented DEA models. The ranks of some schools are quite different under input-oriented and output-oriented DEA models. While there is a 0.728 mean efficiency of type 2 schools under the input-oriented model, there is a 0.668 mean efficiency under the output-oriented model. Sri Chandrarathna Manawa Singha Vidyalaya is fully efficient under the input-oriented model, but it is not fully efficient under the output-oriented model. However, the efficiency score under the output-oriented model is 0.935. But when we consider St. Joseph's College and Terrence N De Silva Maha Vidyalaya, while both schools are fully efficient under the input-oriented model, their efficiency scores are less than 0.5 under the output-oriented model.

The least number of schools including Udahamulla Siddhartha Maha Vidyalaya and Averihena Vidyaloka Kanishta Vidyalaya have efficiency scores less than 0.5. under both input-oriented and output-oriented models. While 4 schools have efficiency scores less than 0.5 under the input-oriented model, 7 schools have efficiency scores less than 0.5 under the output-oriented model. Since more schools have lower efficiency scores under the output-oriented model, schools should pay attention to output maximization utilizing existing inputs rather than input minimization.

Table 1: Technical efficiency scores under VRS of schools

School	Input oriented		Output oriented	
	Efficiency Score	Rank	Efficiency Score	Rank
Madiwela Sri Rahula Maha Vidyalaya	0.75	11	0.657	12
Udahamulla Siddhartha Maha Vidyalaya	0.333	21	0.295	20
Vidyadana Maha Vidyalaya	0.6	15	0.809	9
Rukmale Maha Vidyalaya	1	1	1	1
Sri Chandrarathna Manawasingha Vidyalaya	1	1	0.935	7
Thalahena Maha Vidyalaya	1	1	1	1
Sri Dewamiththa Maha Vidyalaya	1	1	1	1
Welivita St. Mary's Maha Vidyalaya	0.75	11	0.655	13
Sri Indrajothi Vidyalaya	0.3	22	0.625	15
Dedigamuwa Maha Vidyalaya	0.75	11	0.871	8
Sri Sudarshana Vidyalaya	0.5	17	0.735	11
Rathna Kanishta Vidyalaya	0.6	15	0.345	19
Averihena Vidyaloka Kanishta Vidyalaya	0.273	23	0.455	18
Munidasa Kumaratunga Vidyalaya	1	1	1	1
Gothatuwa Maha Vidyalaya	0.783	10	0.643	14
Terrence N De Silva Maha Vidyalaya	1	1	0.464	17
Gamini Vidyalaya	1	1	1	1
St. Joseph's College	1	1	0.201	22
Somadevi Balika Vidyalaya	0.75	11	0.984	6
Ediriweera Sarachchandra Vidyalaya	0.917	9	0.786	10

Weragoda Vidyalaya	0.5	17	0.254	21
Siri Perakumba Vidyalaya	0.5	17	0.08	23
Rajagiriya R.C.T.M. Vidyalaya	0.429	20	0.571	16

Source: Author's calculation using DEA

Input and output targets are presented in Figure 1. According to Ramanathan (2003), input and output targets represent the amount of the given input and output that should be there to achieve the same efficiency score as the most efficient school. Therefore, both input and output targets should be minimized to achieve maximum efficiency level. All the input target values were less than 0.1. Therefore, there were no significant input targets among these schools. Then every type 2 school has a relatively high value of target for output 1 (i.e. percentage of students who passed the O/L examination). However, *Rukmale Maha Vidyalaya* has a relatively lower target value than other schools for output 1. Therefore, except for *Rukmale Maha Vidyalaya*, there was a target in O/L results of these schools to achieve maximum efficiency. On the other hand, *Ediriweera Sarachchandra Vidyalaya* has the highest target value that should account for output 2 (i.e. percentage of students who passed the grade 5 scholarship examination). While other schools have target values between 0 and 0.2, *Thalahena Maha Vidyalaya*, *Munidasa Kumaratunga Vidyalaya*, and *Gamini Vidyalaya* have zero target values for output 2.

Figure 2 represents the input and output slack. The input slack is the difference between the actual input

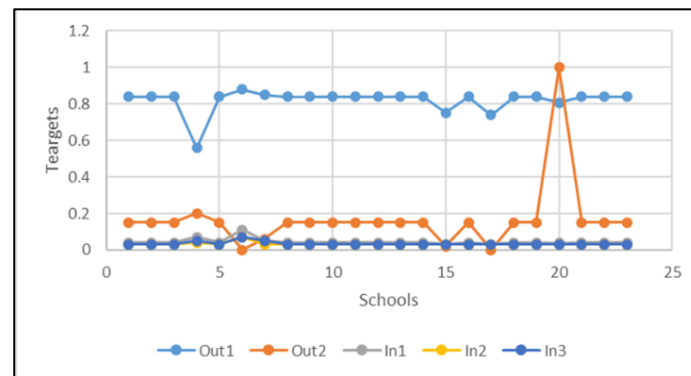


Figure 1: Inputs & outputs targets

and input target, and the output slack is the difference between the output target and actual output (Ramanathan, 2003). Therefore, both input and output slacks should be minimized to achieve maximum efficiency level. Since there are no significant slacks in inputs, it is not necessary to minimize the inputs (i.e. Student-teacher ratio, student-graduate teacher ratio, and student-classroom ratio) in type two schools of Sri Jayawardhanapura education zone. But output 1 (i.e. percentage of students who passed the O/L examination) has high slack values in *Udahamulla Siddhartha Maha Vidyalaya*, *Rathna Kanishta Vidyalaya*, *St. Joseph's College*, and *Siri Perakumba Vidyalaya*. Therefore, the percentage of

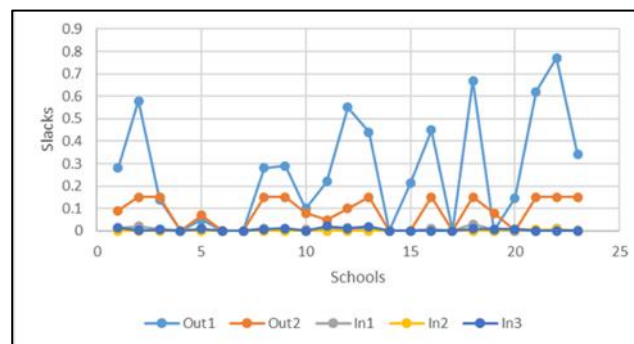


Figure 2: Inputs & outputs slacks

students who passed the O/L examination should be maximized in these schools. Furthermore, output 2 (i.e. percentage of students who passed the grade 5 scholarship examination) has a significant level of slacks. So, the percentage of students who passed the grade 5 scholarship examination should be maximized.

4.1. Results of the Tobit Regression

Table 2 indicates the coefficients, standard error, test statistics, and p-values of the Tobit model. When examining the inputs, the student-teacher ratio significantly negatively influenced the technical efficiency under a 5% significant level ($\beta = -6.2223$, $p < 0.05$). Both the student-class room ratio and student-graduate teacher ratio significantly negatively impacted the technical efficiency under a 10% significant level ($\beta = -7.5302$, -4.1957 , and $p < 0.1$). When considering the efficiency determinants, extra reading books provided by the library significantly positively influenced the technical efficiency under a 1% significant level ($\beta = 0.0246$, $p < 0.01$). Furthermore, Sanitary facilities (toilets) significantly positively influenced the technical efficiency under a 10% significant level ($\beta = 5.9194$, $p < 0.1$).

Table 2: Results of the Tobit regression model

Variable	Coefficient (β)	Standard Error	Test Statistic	P-Value (p)
Constant	1.4257	0.0902	15.8	0.0000
Student-teacher ratio (St)	-6.2223	2.5669	-2.424	0.0153
Student-class room ratio (Sc)	-7.5302	3.8546	-1.954	0.0508
Student-graduate teacher ratio (Sg)	-4.1957	2.1863	-1.919	0.055
Computers (Co)	1.1427	1.1502	0.9934	0.3205
Extra reading books provided by the library (Er)	0.0246	0.0072	3.423	0.0006
Sanitary facilities (Sf)	5.9194	3.4419	1.72	0.0855

Source: Author's calculation by Gretl

$$y_i = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_4 + \beta_5 x_5 + \beta_6 x_6 + u_i \quad (13)$$

$$Te = \beta_0 + \beta_1 St + \beta_2 Sc + \beta_3 Sg + \beta_4 Co + \beta_5 Er + \beta_6 Sf + u_i \quad (14)$$

$$Te = 1.43 - 6.22 St - 7.53 Sc - 4.19 Sg + 1.14 Co + 0.03 Er + 5.92 Sf \quad (15)$$

4.2. Testing whether there any significant deviations in technical efficiency between schools that have equal or less than 250 and more than 250 students in Type 2 schools of Sri Jayawardhanapura education zone.

A hypothesis test was conducted to evaluate mean efficiency differences of schools less than 250 and greater than 250 schools. There is statistical evidence to conclude that a significant mean difference in technical efficiencies between schools that have equal or less than 250 and more than 250 students in Type 2 schools of Sri Jayawardhanapura education zone under 5% significant level ($t(14) = -4.6$, $p = 0.000$) are evidenced

Table 3: Test results for mean difference of schools less than 250 and more than 250 students

T Statistic	DF	P-Value
-4.60	14	0.000

Source: Author's calculation using sampled data

5. Conclusion

According to the DEA results, most Type-2 schools in JEZ were technically efficient. *Sri Indrajothi Vidyalaya* had the lowest efficiency score under the input-oriented DEA model, indicating that its inputs were not utilized efficiently to achieve the given level of output. Similarly, *Siri Perakumba Vidyalaya* had the lowest efficiency score under the output-oriented DEA model, suggesting that its outputs were not maximized with the given level of inputs. However, *Rukmale Maha Vidyalaya*, *Thalahena Maha Vidyalaya*, *Sri Dewamiththa Maha Vidyalaya*, *Munidasa Kumaratunga Vidyalaya*, and *Gamini Vidyalaya* were fully efficient under both input-oriented and output-oriented DEA models. Based on slack values, *Udahamulla Siddhartha Maha Vidyalaya*, *Rathna Kanishta Vidyalaya*, *St. Joseph's College*, and *Siri Perakumba Vidyalaya* should focus on maximizing their G.C.E. Ordinary Level (O/L) results. Additionally, target values suggest that every school, except for *Rukmale Maha Vidyalaya*, should improve their O/L results.

The second stage of the analysis, Tobit regression, identified significant variables influencing the technical efficiency of schools. The student-teacher ratio, student-classroom ratio, student-graduate teacher ratio, number of extra reading books provided by the school library, and sanitary facilities significantly impacted efficiency. However, the number of computers did not show a significant effect. Therefore, resource allocation in Type-2 schools of JEZ should prioritize these significantly impactful factors.

To achieve the second objective of the study, a two-sample t-test was used to evaluate whether a significant mean difference exists in technical efficiency between schools with equal to or less than 250 students and those with more than 250 students in Type-2 schools of JEZ. The results provided sufficient statistical evidence to conclude that such a significant difference exists at a 5% significance level. Since the mean technical efficiency of schools with more than 250 students was higher than that of schools with 250 or fewer students, maintaining an adequate student population is essential to ensure efficiency. Accordingly, ministry of higher education is responsible for implementing relevant policy implication to enhance the level of technical efficiency of schools in terms of fully utilising the public money for education. Future studies can extend the geographical scope of the current study and contribute the literature adding more comparable information.

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**ROLE OF UNIVERSITY INDUSTRY COLLABORATION IN
UPGRADING THE SMALL-SCALE DRY FISH VALUE CHAIN OF
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Abstract: The small-scale dry fish industry in the southern coastal area of Sri Lanka plays a pivotal role in livelihood development and nutritional security. Alongside its importance, this industry is suffering from numerous challenges related to input supply, processing techniques, value chain upgrading, and market access. The study is focused on exploring the role of University -Industry collaboration (UIC) in reducing the challenges of upgrading dry fish value chains to promote sustainable development and economic empowerment of small-scale women fish processors. The Porter's value chain model (Porter, 1985) is used to identify the key bottlenecks and opportunities in the dry fish value chain, and the study is conducted on the south coast of Sri Lanka. The data was collected through structured questionnaires and focus group discussions. Research findings highlight that women dry fish processors are using traditional salt curing and sun drying methods, which are vulnerable to climate risks and quality deterioration issues. The challenges include seasonal variations in fish availability, price fluctuations, poor packaging and storage, and market accessibility. To overcome the challenges, the study suggests that UIC will be a catalyst for knowledge exchange, capacity building, and technology improvement. Focus group discussions, workshops, and online market introductions help to improve financial literacy, quality assurance, and product diversification. Women fish processors were encouraged to develop their own brand, "Pink Fish," which was developed to improve market access and promotions. The key finding of the study is the significance of the UIC for innovation, reducing the knowledge gap, and empowering fishermen to overcome challenges by contributing to the sustainable growth of the dry fish industry in south coast Sri Lanka.

Keywords: University-Industry Collaboration; Dry fish; Value chain; Women

1. Introduction

Fish is a major source of animal protein intake for humans which is consumed in different forms such as fresh, frozen, dried, and smoked. According to the Food and Agriculture Organization of the United Nations (FAO, 2020), approximately 17Mt of fish were consumed in the form of dried, salted, or smoked around the world. Drying is a well-known method of food preservation, as well as being used to reduce post-harvest loss.

Dried fish is very popular in developing countries rather than developed countries since it is a low-cost protein. Bangladesh, Thailand, India, and China are the largest dry fish producers in the world (Rasul et al., 2020). Dried fish production mainly provides employment for poor livelihoods (Kallon et al., 2017) in Asian countries.

The small-scale dry fish industry plays a pivotal role in rural economies in South Asian countries such as India, Sri Lanka, and the Maldives. It provides financial support to the majority of fisherman communities in coastal areas. The industry mainly faces the absence of storage facilities, rural road infrastructure, preservation facilities, insect infestations, and product-standard testing facilities.(Giri, A., & Biswas, 2018). Sri Lanka is using traditional fish drying methods such as salting and sun drying which are comparatively cost-effective for small-scale producers(Das et al., 2013; Sugathapala et al., 2012). This industry has potential growth opportunities since it is a major protein supply method for developing countries and it requires government and other institutional support to improve and modernize their processing techniques(Giri, A & Biswas, 2018).

There are nearly 20 livelihood zones in Sri Lanka. Each livelihood zone of Sri Lanka is classified based on the level of food security (WFP and HARTI, 2015), accordingly, the Southern coastal area is named LK03 Southern Coastal Tourism and Fishing Zone. Households in this coastal area mainly engage in fishing-related livelihood activities (WFP and HARTI, 2015). As coastal fishing is a highly climate-sensitive livelihood approach, the income of fishing communities is threatened by climate hazards or extreme weather events (FAO and WFP, 2017). According to Sri Lankan food security and resilience level mapping, the Southern coastal zone is considered as an occasional food insecure zone. It implies that this southern coastal area is subjected to occasional climate-related hazards, resulting in livelihood disruptions and eventually rising food insecurity (WFP and HARTI, 2015).

Universities have been identified as the key to the wealth creation of a country since they are the center for the best minds of the country (Moscardini et al., 2022). The university's profile as a non-profit organization has made the experts of certain fields of knowledge unknown to the industry and thus, their expertise was not fully utilized for the betterment of society it is recognized as a catalyst for innovation, knowledge exchange, and economic growth(Ramli & Zainol, 2013). The University-industry collaboration (UIC) benefits both university and industry partners. Universities are gaining access to financial resources and research opportunities, while industries accelerate their innovation processes. Major aspects of UIC consist of collaboration objectives, intellectual property management, mechanisms, stakeholders, challenges, and success factors(Bonab et al., 2024). However, UIC is facing challenges such as cultural differences and intellectual property disputes, which can hinder successful collaborations(Ramli & Zainol, 2013). The overall outcome of UIC consists of a win-win strategy that fosters technological advancements, creates skilled graduates, and stimulates private-sector investments in research and development(T. Mgonja, 2017).

UIC plays a crucial role in upgrading Sri Lanka's small-scale industries, including the dry fish value chain. While current UIC links are mostly short-term and informal, there's a growing trend towards more substantial collaborations like joint research and development activities(Larsen et al., 2016) In recent years, the concept of UIC has gained significant attention as a mechanism for driving innovation,

enhancing productivity, and fostering sustainable development. The collaboration between universities and industries helps bridge the gap between theoretical research and practical application.

The dry fish industry is facing not only opportunities but also challenges in the value chain upgrading. Studies from the Asia and Africa region state that the complexity of these value chains involves multiple actors (Neranjala et al., 2022; Okumu, 2009; Upadhyay et al., 2017; Wicaksana et al., 2022). This industry significantly affects providing employment to the rural economy (Neranjala et al., 2022), and updating strategies may include not only product development but also functional upgrades. In the context of product development, it includes product improvements through better packaging, process enhancements via technology adoption, and also as functional improvements industry can be upgraded to direct selling and online selling (Wicaksana et al., 2022). For the sustainable development of the industry, stakeholders must take initiatives like aquaculture investment and implement quality control measures throughout the value chain (Neranjala et al., 2022; Okumu, 2009).

The role of UIC in upgrading the small-scale dry fish value chain in southern Sri Lanka is a critical area of focus due to the industry's significant contribution to the livelihoods and nutritional security of coastal communities. The small-scale dry fish sector, historically reliant on traditional preservation techniques such as sun-drying and salting, supports local diets and cultural practices, yet faces numerous challenges, including poor working conditions and insufficient market access for women, who constitute a large part of the workforce in this sector (Galappaththi et al., 2023).

In the context of the dry fish value chain, universities can contribute by providing research-driven insights into sustainable practices, quality control, and market trends. This engagement not only benefits industries by improving their operational efficiency but also enhances the educational experience for students through real-world applications of their studies.(Tommasi et al., 2021).

The UIC in the dry fish industry is presenting its potential to address socio-economic and environmental factors when upgrading value chains in the industry. Projects such as “Dried Fish Matters” are exploring the socio-economy in the region collaborating with multiple institutions (Galappaththi et al, 2023; Johnson, 2018). The UIC aims to enhance well-being, nutrition, and food security while addressing the sector's invisibility in research and policy(Ghosh et al., 2023) and these studies identified that well-being, nutrition, and food security while addressing the sector's invisibility in research and policy(Giri, A., & Biswas, 2018). This research suggests that UIC practices forge just transitions in the dried fish sector, emphasizing the need for knowledge co-production and participatory approaches involving fishers, scientists, and other stakeholders(Ghosh et al., 2023). Universities can also contribute by conducting research on improved drying techniques, developing cost-effective technologies, and providing training on quality assurance and food safety standards. On other hand industry partners are contributing to the study by offering their insights into market demands, facilitating the adoption of innovations, and providing access to distribution networks.

This study therefore examines the contribution of academics to the promotion of university-industry knowledge exchange in Sri Lanka. The main objectives of the study are to explore the dry fish value chain and map the dry fish value chain, finding out the bottlenecks of dry fish value chain, special reference to the input supply, fish processing, value addition, and market access, and Dry fish value chain upgrading: knowledge and capacity building. The paper is organized as follows. The next section presents research methodology which is followed by an analysis of our empirical research findings, before presenting conclusions and discussing implications in the final section.

2. Materials and Methodology

The research explores the role of university-industry collaboration in enhancing the small-scale dry fish value chain in Southern Sri Lanka. Small-scale dry fish processors face challenges related to input

supply, processing techniques, value addition, and market access. The study adopts a deductive research approach, utilizing Porter's Value Chain Model (Porter, 1985) to analyze the dry fish value chain in Southern Sri Lanka. The research focuses on 37 dry fish processors from Ambalangoda and Kudawella, selected through a purposive sampling method to ensure relevance to the study. Data was collected through field surveys and focus group discussions (FGDs). Surveys were used to achieve quantitative data, while FGDs provided in-depth insights into input supply (main fish processing seasons and species availability), fish processing (methods, volumes), value addition, and market access bottlenecks. Based on these findings, workshops and training programs were organized to enhance knowledge and capacity building, with a focus on upgrading the value chain through university-industry collaboration. Data analysis was carried out using Microsoft Excel, where quantitative data from surveys were statistically examined, and qualitative data from FGDs were analyzed thematically to highlight key issues and opportunities within the dry fish value chain.

3. Results & Discussion

Inbound logistics involves sourcing fresh fish from fishermen, transporting raw fish to drying locations, storing fish before processing, and supplying inputs such as salt and packing materials for storage (Figure 1). Fish processors in Ambalangoda, and Kudawella followed key steps to ensure quality. They sourced fresh fish from local fishermen, including Balaya (*Katsuwonus pelamis*), Linna (*Sardinella gibbosa*), Pothubari (*Decapterus russelli*), Wanna (*Pampus argenteus*), Kelawalla (*Thunnus albacares*), Moru (*Selar crumenophthalmus*), Alagudu (*Lethrinus nebulosus*), and Sprats (*Sprattus sprattus*) as these varieties were ideal for drying. Transporting the fish quickly using walking, motorbikes helped maintain freshness. Before drying, fish were stored properly in coolers, sheds, or drying areas to prevent spoilage. Essential inputs like salt for preservation and packing materials for storage and sales were procured to ensure smooth processing and distribution.

Operations involved transforming fresh fish into dried fish through cleaning, drying, preservation, and hygiene maintenance (Figure 1). Fish processors in Ambalangoda, and Kudawella followed these steps to ensure quality and efficiency. **Fish were cleaned and prepared** by washing, gutting, and splitting to remove dirt and improve drying. The **main drying method was sun drying**, where fish were spread on racks, and mats under direct sunlight. This traditional method was cost-effective and removed moisture to prevent bacterial growth, extending shelf life. **Salt application** was used for preservation, either by dry salting or brining. Salt helps prevent spoilage, enhances flavor, and improves texture (Fitri et al, 2022). The amount used depended on fish type and market demand. **Hygiene maintenance** was crucial to ensure food safety. Processors kept drying areas clean, used proper racks, and handled fish with sanitized tools to prevent contamination from dust and pests. These measures helped produce high-quality dried fish.

Outbound logistics involves distributing dried fish and Maldives fish to consumers, retailers, and wholesalers (Figure 1). Fish processors transported their products using motorcycles and on walking. Many buyers also visited processing sites to purchase directly, reducing intermediaries and increasing profits. Marketing and sales involve direct sales, market rate as pricing strategy, and word-of-mouth as promotion strategy (Figure 1). Fish processors in Ambalangoda and Kudawella used **direct sales** as their primary selling method, where they sold their products directly to consumers, retailers, and wholesalers without intermediaries. For pricing, they followed the **market rate strategy** by adjusting their prices based on current market conditions to stay competitive. This ensured fair pricing for both sellers and buyers. Promotion mainly relied on **word-of-mouth marketing**, where satisfied customers spread the reputation of their dried fish products. This traditional method helped build trust and attract more buyers within their communities.

Services involve maintaining quality, ensuring consumer satisfaction, and handling feedback (Figure 1). Fish processors in Ambalangoda and Kudawella prioritized **product quality** by using hygienic practices to preserve the freshness of dry fish and Maldives fish. To **ensure consumer satisfaction**, they focused on consistent quality, proper packaging, and timely delivery. Additionally, they actively **address complaints and feedback**, making improvements based on customer preferences to enhance trust and market competitiveness. Firm infrastructure includes governance and institutional supports (Figure1). InKudawella, **Sanasa Cooperative Bank and RDB Bank provide loans and savings facilities**, helping processors to improve their fish processing.

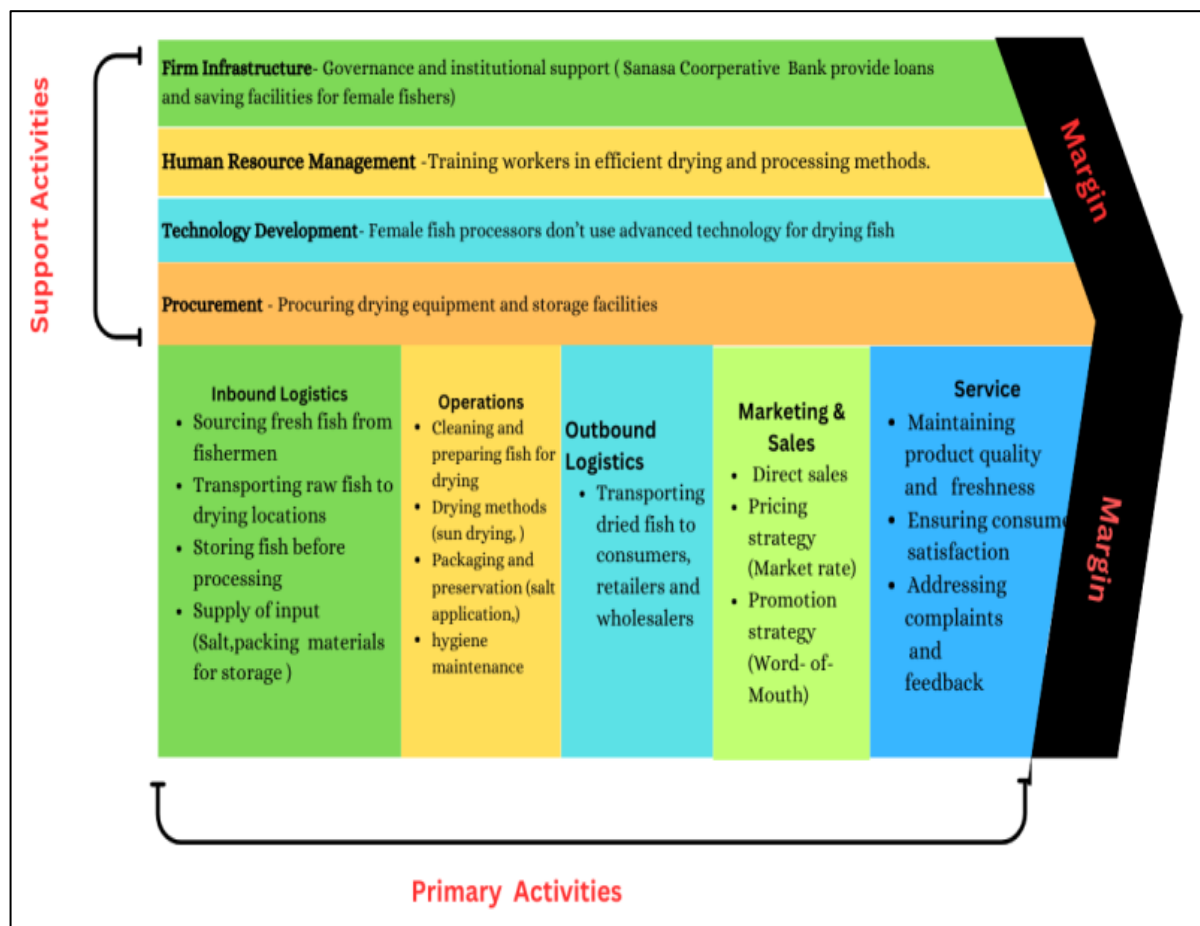


Figure 1: Dry Fish Value Chain Mapped Using Porter's Value Chain Model

Fish processors in Ambalangoda, and Kudawella **train workers in sun-drying and processing** based on their **experience**, improving efficiency and product quality. Fish processors in these areas **didn't use advanced technology for their production** due to a lack of awareness and knowledge of advanced technology. Fish processors in these areas **procured basic drying equipment** to support sun-drying.

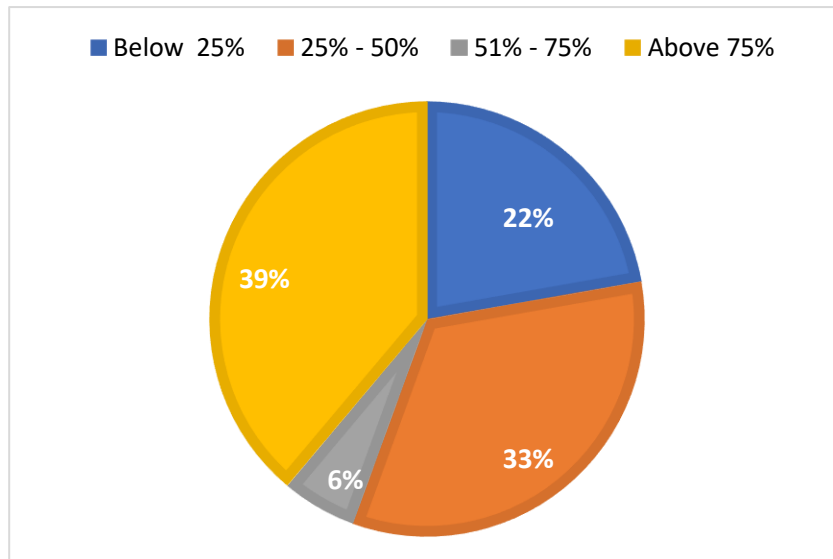


Figure 2: Fish processors' contribution to household income

Figure 2 indicates that 39% of fish processors contribute more than 75% of household income, suggesting that many are the primary earners, likely due to limited alternative income sources within their families (Harper et al,2013). 33% contribute 25% - 50%, indicating that a significant percentage plays a supporting but not primary financial role. This pattern suggests that fish processors are essential to household financial stability, particularly in lower-income families (Atkins et al., 2021).

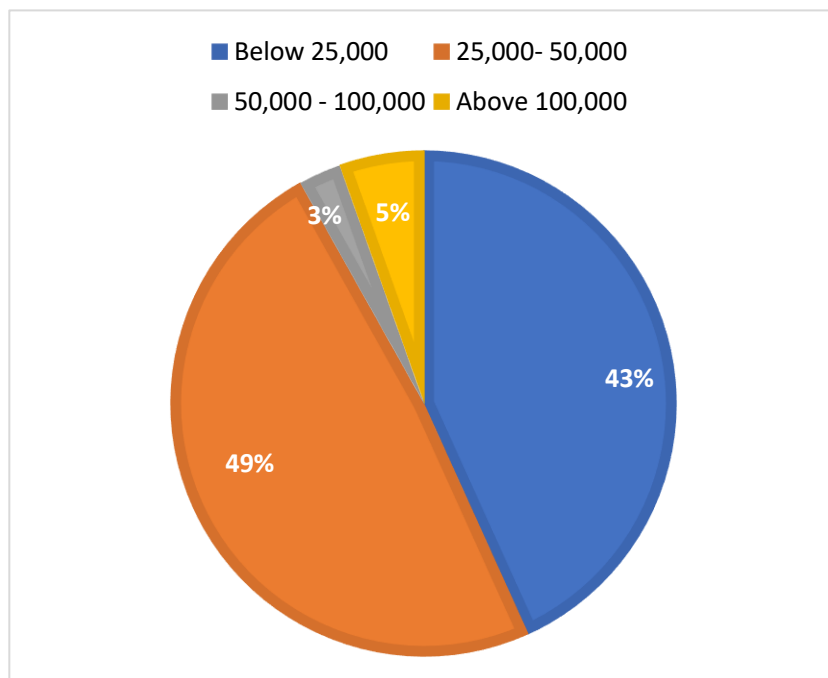


Figure 3: Household Income Level

Figure 3 indicates the household income level distribution, where **43% of households earn below 25,000**, highlighting a large percentage of the population living in lower-income conditions. Of the sample, **49% of households earn between 25,000 - 50,000**, indicating the majority of families in the middle-income level, which suggests a moderate standard of living but still potential financial constraints. However, **5% of households earn above 100,000**, indicating that a very small group enjoys a higher standard of living. The distribution emphasizes that most households are concentrated in the lower to middle-income ranges, with only a few reaching higher income levels (Atkins et al., 2021).

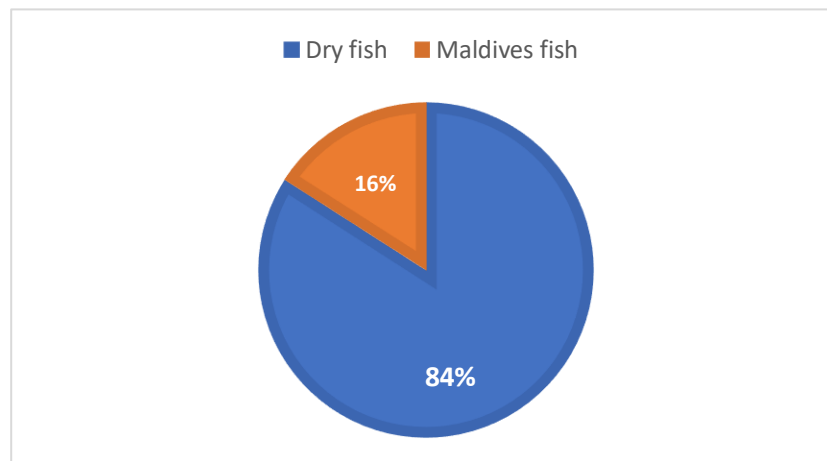


Figure 4 Types of Products Produced by Fish Processors

Figure 4 indicates that 84% of products are dry fish, reflecting its dominance in the market due to its long shelf life and high consumer demand (Siddhnath et al, 2024). Of the sample, 16% were Maldives fish, which, while less common, likely caters to niche markets or specific preferences (Fathimath & Milne, 2011). This highlights dry fish as the primary product, with Maldives fish serving as a smaller, specialized category (Galappaththi, 2022).

Figure 5 indicates that Linna (*Sardinella gibbosa*), Pothubari (*Decapterus russelli*), and Balaya

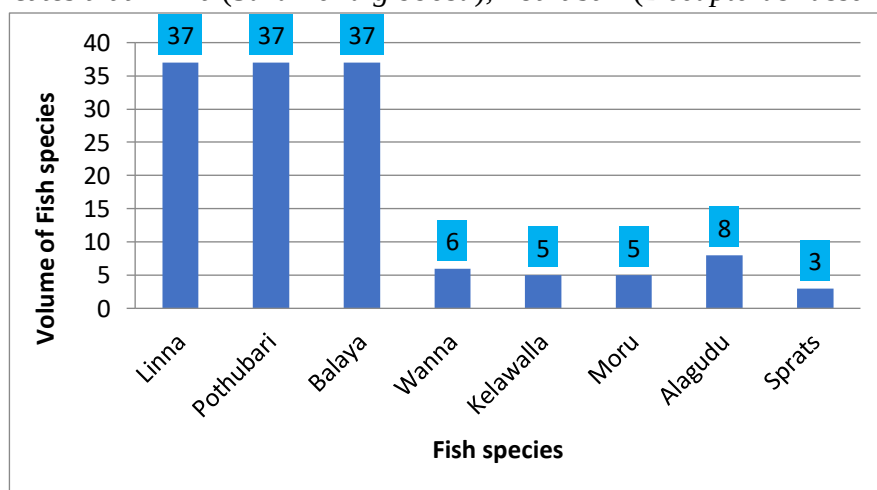


Figure 5 Fish Species Processed by Fish Processors

(*Katsuwonus pelamis*) are the most commonly processed fish species, each with 37 units, indicating their high availability. Sprats, with only 3, are processed the least, likely serving niche markets (Silovs, 2018).

Problem tree analysis- identify problems and gaps

The dry fish processing industry faces significant challenges that make it both unstable and unprofitable. The core issue (Figure 6) stems from bottlenecks throughout the value chain, beginning with input supply. A major problem is the high cost of raw fish, which fluctuates seasonally, making it difficult for processors to maintain consistent production. From January to May, fish are more affordable and available, but from May to January, fish scarcity leads to higher prices. This, coupled with limited financial access and rising salt prices, further exacerbates the financial strain on processors, as they cannot buy fish in bulk during peak seasons when prices are lower.

Fish processing itself also faces numerous challenges, primarily due to weather dependency, as processors rely heavily on sun drying, which is highly vulnerable to rain, floods, and cyclones, leading to spoilage and financial losses. Furthermore, quality control issues arise due to contamination from dust, pests, and open-air drying methods, with poor drying infrastructure exacerbating the problem. The industry also suffers from a lack of exposure to modern drying technologies like solar or mechanical dryers, which limits the efficiency and consistency of production. Value addition in the industry is constrained by a lack of knowledge and skills, with many processors continuing to use traditional methods without innovating to improve product quality. Additionally, processors face challenges in accessing proper packaging, which affects both product preservation and market appeal. Consumers are often unaware of value-added products, preferring traditional sun-dried fish instead of new product variations, which further limits market growth.

Market access barriers are also a major obstacle. Price fluctuations resulting from changes in fish supply make it difficult for processors to maintain stable income, while high competition from large suppliers intensifies the struggle for small-scale processors. The lack of branding and packaging reduces the attractiveness of dry fish products, and transportation issues restrict access to distant markets due to high costs and poor facilities. Furthermore, the limited marketing knowledge of processors prevents them from reaching broader markets, relying instead on traditional selling methods. Lastly, the lack of buyer connections limits opportunities for processors to access supermarkets or export markets, further restricting their growth potential.

The effects of these bottlenecks are far-reaching. Economically, processors experience inconsistent income and higher production costs, which significantly reduce profitability and limit growth potential for small-scale businesses. Product quality is also compromised, with poor hygiene leading to food safety concerns and a shorter shelf life, which in turn decreases market demand. Market limitations, including difficulty competing with larger suppliers and restricted market reach, hinder the growth of small-scale processors. Environmentally and socially, the industry faces increased fish wastage during rainy seasons, and the dependency on outdated processing methods prevents the industry from advancing and improving.

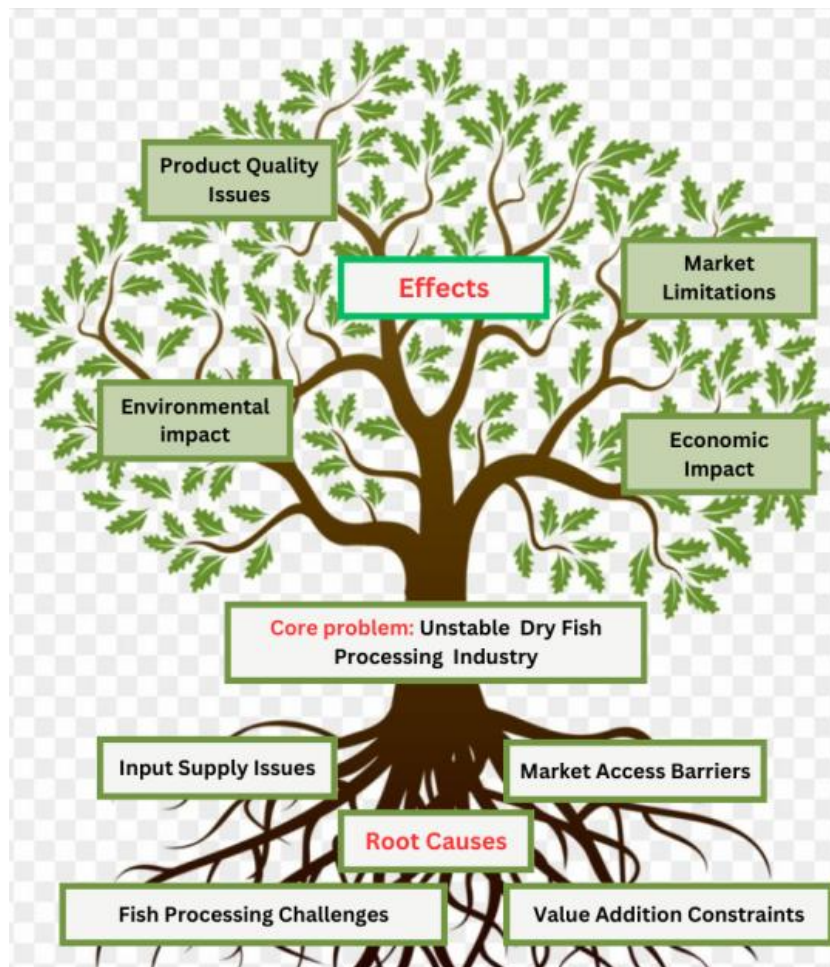


Figure 6: Problem tree analysis

The bottlenecks of the dry fish value chain, with special reference to the input supply, fish processing, value addition and market access

Figure 7 indicates the bottlenecks of the dry fish value chain, with special reference to the input supply, fish processing, value addition and market access. One major issue was the high cost of raw fish, which changes with the seasons. From January to May, fish were more available and affordable. However, from May to January, fish became scarce, making prices go up. This made it difficult for processors to keep production steady. Financial difficulties were another big problem. Many fish processors had limited access to loans and extra money to invest in their businesses. Without enough funds, they struggled to buy fish in bulk during the peak season when production was low. These days, the rising price of salt has also added to their challenges. Since salt is necessary for preserving fish, higher prices increased production costs and reduced profits.

One major challenge was **weather dependency for drying**, as all processors used sun drying, making their production highly vulnerable to heavy rain, floods, and cyclones. During prolonged rainy periods, they experienced significant losses due to spoilage and the inability to dry fish properly. Another critical issue was **quality control**, as maintaining hygiene and food safety was difficult. Fish are often exposed to dust, pests, and contamination during open-air drying, which affects the final product's quality and shelf life. The lack of proper drying racks and protective coverings further increased the risk of contamination. Additionally, there was a **lack of knowledge of advanced technology**, as all processors

relied on traditional drying methods without exposure to modern alternatives like solar or mechanical dryers. This limited their ability to improve efficiency, maintain consistent quality, and expand production.

A major bottleneck was the lack of awareness and skills among fish processors, as they primarily relied on traditional drying methods and had limited knowledge of advanced techniques. Without proper training, they were unable to innovate higher-value products. Another significant issue was the limited access to suitable packaging materials, which affected product preservation and market appeal. Proper packaging could enhance shelf life and attract more consumers, but the high cost and unavailability of quality materials made it difficult for processors to adopt better packaging solutions. Low consumer awareness further compounded the issue, as many customers were unfamiliar with the benefits of value-added dry fish products. Since traditionally sun-dried fish was widely accepted, there was little demand for new product variations.

Market access in the dry fish value chain faced several bottlenecks that limited growth and profitability for small-scale fish processors. Price fluctuations were a major challenge, as the price of dry fish changed frequently due to seasonal variations in fish availability and market demand. When supply increases, prices drop, reducing profit margins. High competition from large suppliers further intensified the struggle, as big suppliers had better facilities, bulk production, and strong market connections, allowing them to offer lower prices and capture a larger market share. Additionally, the lack of branding and packaging affected marketability, as many processors sold their products without proper packaging or brand identity, making it difficult to attract new customers and justify higher prices. Transportation challenges also played a significant role, as poor transport facilities and high costs restricted access to distant markets, forcing processors to rely on local buyers. Moreover, the lack of marketing knowledge meant that most processors depended on traditional selling methods like word of mouth, missing opportunities to reach broader markets through modern strategies. Finally, limited buyer connections further restricted market expansion, as processors primarily sold to

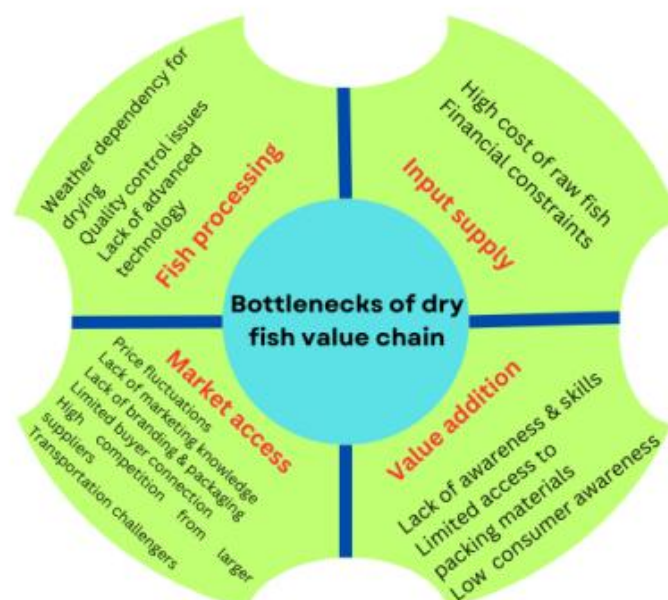


Figure 7: The bottle necks of dry fish value chain, special reference to the input supply, fish processing, value addition and market access

local consumers, retailers, and wholesalers who came to them, rather than actively seeking larger buyers, supermarkets, and export opportunities.

Brief on capacity -building work

The workshops were conducted in Ambalangoda and Kudawella to upgrade the dry fish value chain by enhancing the knowledge and capacity of fish processors. Each workshop had 25-30 participants and focused on improving financial literacy, market access, and value-addition techniques. In Kudawella, they engaged with the Sanasa Cooperative Bank, which is led by women and provides loans and savings facilities to fish processors. In Ambalangoda, a team of university academics held focus group discussions with women leaders involved in lending money, local fishermen, and bank managers to understand financial management practices and available banking services.

To support financial management, university academics developed a user-friendly mobile application that allowed real-time tracking of expenses, categorized spending, and set savings goals. This tool helped participants manage their income efficiently and prepare for future financial risks. Additionally, we introduced the concept of savings groups and a community disaster fund to provide financial security during climate-induced emergencies. These initiatives encouraged collective financial resilience within the fishing community.

Workshops organized by university academics focused on value addition in fish processing, a topic that most participants were unfamiliar with. We provided hands-on demonstrations, brochures, and leaflets to teach techniques for creating higher-value fish products. One major concern was the lack of proper storage, leading to spoilage. To address this, a lecturer conducted a practical session on preserving dried fish and proper cutting techniques to minimize waste.

Furthermore, a workshop was conducted on market creation, financial literacy, and financial entrepreneurship to help participants identify new market opportunities, improve financial decision-making, and develop business skills. Interactive exercises and real-life case studies helped them apply these strategies to their businesses. The workshops were held over two days, with contributions from university lecturers, the Small-Scale Fisheries Association of Sri Lanka, the Ministry of Fisheries, NGOs like NAFSO, and financial institutions. These efforts collectively empowered fish processors, equipping them with the skills and knowledge to enhance their businesses and financial stability.

Market entry strategies: value addition, branding, packaging and promotion

Three value-added products-: bottled Maldive fish flakes, Ambulthiyal (traditional black fish curry) in clay pots and Jadi (salt curing) in bottles (Figure 9) were introduced to the market with new packaging and brand name, Pink Fish (Figure 8), improving their income opportunities and confidence. Getting a stall at the Matara Good Market was a big success, giving them their first real market experience and exposure. Our team helped by design the business logo, product labels, and advertisements, making the brand more recognizable and professional. These products were sold via the Matara Good Market.



Figure 8: Pink Fish brand



Figure 9: Types of products under Pink Fish brand produced by fish processors

We created important partnerships by linking fish processors with key organizations like the Sri Lanka Centre for Development Facilitation, Cargills, and NGOs, which provided support and funding. To help with financial management, we introduced community-based savings mechanisms as a simple alternative to technology. Working with university lecturers and NGOs also helped connect academic knowledge with real-life practice, making the project even more effective.

4. Conclusion

The study explored and mapped the dry fish value chain of the south coast of Sri Lanka using Porter's value chain model. The study identified the key stakeholders of the dry fish value chain, especially primary activities and support activities. The dry fish value chain in this area depends on traditional salt curing and sun-drying methods, which are highly susceptible to climate change. Several bottlenecks were identified in the value chain specifically in inputs, processing, value addition, and market access. Seasonal market fluctuations and rapid changes in raw fish prices, and rising input costs are the significant challenges in input supplies. Inadequate infrastructure, and quality control issues compromise the consistency and safety of products. Lack of skills in product innovation and packaging hinders value addition, while poor branding, transportation difficulties, and restricted market access reduce competitiveness and growth opportunities for small-scale processors. To address the above challenges and upgrade the value chain, capacity-building initiatives focused on knowledge transfer, skills development, and technological support are critical. The role of University Industry Collaboration can play a pivotal role in enhancing technical expertise, training on modern processing techniques, and practical business skills. Workshops to introduce new technologies and modern financial management initiatives may reduce the bottlenecks of the dry fish industry. Also, these interactive activities with the community may help small-scale processors enter broader markets and improve their income opportunities.

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INNOVATIVE ECO-FRIENDLY SUPERHYDROPHOBIC COATING FOR POLYESTER UMBRELLA FABRICS: ENSURING LONGEVITY AND WATER RESISTANCE

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Abstract: The demand for durable and eco-friendly materials in outdoor products has led to the development of advanced coatings that enhance the performance of fabrics. In this study, we present an innovative, eco-friendly superhydrophobic coating designed to improve the water resistance and longevity of polyester umbrella fabrics. The coating was prepared using tetraethyl orthosilicate (TEOS) and Hexadecyltrimethoxysilane (HDTMS) via a sol-gel process, which could be applied using a coating sponge on the fabric. The coating consists of a multi-layered, porous nano-micro structure formed through the random arrangement of modified spherical SiO₂ nanoparticles at the thread junctions of the fabric. This unique structure significantly boosts the water-repellent properties of the fabric, achieving an outstanding water contact angle of 163°±2° and a low water sliding angle of 8°, confirming its excellent hydrophobicity. In addition to its water resistance, the treated fabric exhibited a remarkable increase in tensile strength by 50 MPa, while maintaining stable hydrophobicity across a broad pH range from 5 to 11. The superhydrophobic fabric could withstand a 0.5 cm diameter water jet with 100 kPa pressure for 40 minutes and demonstrated impressive abrasion resistance, with the fabric retaining its water-repellent properties even after 150 abrasion cycles on sandpaper. Furthermore, the fabric showed effective self-cleaning abilities, efficiently repelling contaminants like mud, sauces, and beverages. These results highlight the potential of this eco-friendly coating to enhance the performance and longevity of polyester umbrella fabrics, offering both functional and sustainable solutions for outdoor textile applications.

Keywords: Eco-friendly; Hexadecyltrimethoxysilan; Self-cleaning; Superhydrophobic polyester; Tetraethyl orthosilicate

1. Introduction

Superhydrophobic surfaces and coatings have garnered substantial attention in recent years due to their exceptional and diverse range of applications, such as anti-corrosion, anti-icing, anti-fogging, oil-water separation, and self-cleaning (Li *et al.*, 2019; Yoon *et al.*, 2020; Sha *et al.*, 2021; Romero-Montero *et al.*, 2023). These surfaces are defined by a water contact angle (WCA) greater than 150° and a water sliding angle (WSA) of less than 10° , which together enable water droplets to form near-perfect spheres that roll off the surface with minimal resistance (Qu *et al.*, 2016; Fei *et al.*, 2020). The unique properties of superhydrophobic surfaces result from an intricate interplay of two primary factors: low surface energy and significant surface roughness (Parvate, Dixit and Chattopadhyay, 2020; Teng *et al.*, 2020). The roughness of a surface creates a micro-nanoscale texture that reduces the area of contact between the water droplet and the surface, promoting the formation of air pockets at the surface interface (Sotoudeh *et al.*, 2023). Simultaneously, the low surface energy of the material repels water, further enhancing the hydrophobic effect (Pan *et al.*, 2024). When combined, these factors create a surface that is highly resistant to wetting, enabling the water droplets to sit atop the surface in a nearly spherical form.

Perfluorinated compounds, such as fluorosilanes and fluorocarbon molecules, have been widely used in creating superhydrophobic surfaces due to their ultralow surface energy ($\approx 10 \text{ mJ m}^{-2}$) (Mohamed, Ezzat and Abdel-Gaber, 2022). These materials are highly effective at repelling water; however, their environmental and health impacts have raised significant concerns (Nørgaard *et al.*, 2014). Long-chained fluorocarbons, in particular, are toxic, persistent in the environment, and prone to bioaccumulation and biomagnification, which can result in harmful ecological consequences (Du *et al.*, 2021; Brunn *et al.*, 2023). In response to these challenges, recent research works have focused on developing fluorine-free superhydrophobic treatments. Studies have explored various approaches, such as the use of SiO_2 and polystyrene coatings created through different solution systems, as well as polydimethylsiloxane (PDMS) combined with carbon microspheres or graphene oxide (Zhang *et al.*, 2013; Mohamed, Ezzat and Abdel-Gaber, 2022). However, many of these methods still rely on organic solvents that are toxic, non-eco-friendly, and expensive. The need for superhydrophobic surfaces created using water-based, fluorine-free solvents has become increasingly critical. Despite advancements in waterborne superhydrophobic surfaces, challenges related to durability, complex preparation processes, surface compatibility, and high costs persist, limiting their widespread application (Elzaabalawy and Meguid, 2020; Luo and Li, 2023). In recent years, hexadecyltrimethoxysilane (HDTMS), an organosilane-based surface modifier, has been increasingly employed in the fabrication of superhydrophobic coatings, particularly for waterborne systems (Chang *et al.*, 2015; Sohrabi, Mansouri and Khalifan, 2019). While HDTMS offers promising hydrophobic properties, recent experimental studies have demonstrated that coatings produced using conventional methods exhibit suboptimal durability and reduced water repellency (Handajani, Widati and Yusbainika, 2019; Das, Roy and Ghosh, 2023). These limitations underscore the necessity of developing innovative strategies that can more effectively harness HDTMS to enhance both the longevity and superhydrophobic performance of the coatings. Specifically, there is a critical need to achieve higher water contact angles and improved resistance to environmental degradation to realize the full potential of HDTMS-based surface treatments.

Creating superhydrophobic surfaces for umbrella fabrics is a critical functional requirement, as it enables rapid water repellency, allowing the umbrella to remain dry and be conveniently stored in bags, vehicles, on tables, or on floors without dripping residual water (Tian *et al.*, 2024). Polyester fabric, a synthetic polymer primarily derived from petroleum-based resources, is widely utilized in the manufacture of commercial umbrellas due to its exceptional durability, tensile strength, flexibility, and resistance to various environmental conditions (Kumar and Senthil Kumar, 2020; Sfameni *et al.*, 2023). Conventional hydrophobic textile finishes, typically based on fluorinated compounds, have been effective in improving water repellency but raise significant environmental and health concerns due to

their persistence, bioaccumulation, and toxicity (Ghosh and Pallye, 2020; Xie *et al.*, 2021; Sfameni *et al.*, 2023). In this study, we propose a facile, cost-effective method for fabricating superhydrophobic coatings on polyester umbrella fabric using HDTMS as the key hydrophobic agent. The technique involves a simple sponge-based application process, offering a practical, scalable solution suitable for both laboratory research and potential commercial deployment.

2. Methodology

2.1. Materials

Tetraethyl orthosilicate (TEOS, 98% purity; SiO₂ content: 28–28.8%) was procured from Access Labtech (Pvt) Ltd., Sri Lanka. Hexadecyltrimethoxysilane (HDTMS, 96% purity) was obtained from Organic Trading (Pvt) Ltd., Sri Lanka. Ammonium hydroxide (NH₄OH, 95%), isopropyl alcohol (IPA, 99%), polyester fabric (PF), and coating application sponges were sourced from the local market in Sri Lanka. All reagents and materials were used as received, without any further purification.

2.2. Preparation and Application Process of Superhydrophobic Coating on Polyester Fabric

Initially, 6 ml of NH₄OH was mixed with 80 ml of IPA and stirred magnetically at 50 °C for 30 minutes. Subsequently, TEOS was added dropwise to the mixture and stirred continuously at 50 °C for an additional 1 hour. Following this, HDTMS was added dropwise to the reaction mixture using a micropipette, at a concentration of 1% (w/w). The resulting mixture was stirred for a further 3 hours under the same temperature conditions. After stirring, the solution was left to stand overnight at room temperature to ensure complete reaction. The resulting sol-gel was then diluted with IPA in a 1:1 volume ratio.

The prepared superhydrophobic sol was applied to PF using a sponge applicator. The coated fabric was subsequently dried using a hot air flow for 10 minutes. The treated superhydrophobic PF was then subjected to various characterization techniques to evaluate its properties.

2.3 Characterization

The surface morphology and elemental composition of both modified and unmodified PFs were analyzed using a ZEISS EVO 18 analytical scanning electron microscope (SEM) coupled with energy-dispersive X-ray spectroscopy (EDX) for elemental mapping. Chemical characterization of the PF samples was performed using a Bruker Vertex 80 Fourier Transform Infrared (FTIR) spectrometer. These analyses were conducted at the Faculty of Technology, University of Colombo, Homagama, Sri Lanka. The hydrophobicity of the treated fabrics was evaluated by measuring the water contact angle (WCA) using a Krüss DSA25S Drop Shape Analyzer and surface topography of the engineered PFs were examined using a Park Systems XE-100 Atomic Force Microscope (AFM) at the Sri Lanka Institute of Nanotechnology (SLINTEC), Homagama, Sri Lanka.

The tensile strength of both treated and untreated PFs was evaluated using an Instron 3365 Universal Tensile Tester at the SLINTEC, Homagama, Sri Lanka. The fabric specimens were prepared with dimensions of 8 cm × 1 cm for consistency during measurement. The mechanical abrasion resistance of the superhydrophobic PF was evaluated using a custom-built abrasion testing apparatus. A 50 g load was applied to the fabric surface, which was abraded against 1000-grit sandpaper to simulate mechanical wear. The self-cleaning performance of the treated PF was assessed by applying a drop of mud to the surface and subsequently introducing water droplets, observing whether they could roll off and remove the contaminant effectively. To examine the durability of the superhydrophobic coating, the static water contact angle was measured after subjecting the fabric to various environmental and chemical stresses. These included exposure to strong acidic and basic solutions, as well as common everyday substances such as sauces and beverages including tea, milk, malted beverages, and food

dyes. Washing stability was evaluated by subjecting the coated fabrics to a continuous water jet with a 0.5 cm diameter at a pressure of 100 kPa, applied in 10-minute intervals.

3. Results and Discussion

3.1 Surface Morphology, Roughness and Chemical Composition

The SEM image analyses were employed to evaluate the surface morphology of PF before and after the application of the superhydrophobic coating. The untreated PF (Figure 1a & b) exhibited a smooth and uniform surface, characteristic of the orderly interlacing of synthetic fibers in a well-defined network. This regular morphology results in low surface roughness, limiting the entrapment of air and thereby contributing to weak inherent water-repellent properties. Following the coating treatment, notable morphological changes were observed in the SEM images of the modified PF (Figure 1c–f). The surface displayed a distinct hierarchical micro/nano-scale architecture, arising from the non-uniform deposition of functionalized SiO₂ nanoparticles and micro-agglomerates ranging from 60 nm to 3 μm. These structures were predominantly concentrated at fiber junctions and distributed along the thread surfaces, forming a rough, porous, and multilayered topology. This dual-scale roughness significantly enhances surface texturing and facilitates the formation of air pockets within the surface features. Combined with the low surface energy of the coating material, this morphology effectively reduces the contact area between water droplets and the fabric, in alignment with the Cassie–Baxter wetting model (Pan *et al.*, 2024). Consequently, the treated PF exhibits markedly improved water repellency, confirming the successful induction of superhydrophobic behavior through nanoscale surface modification.

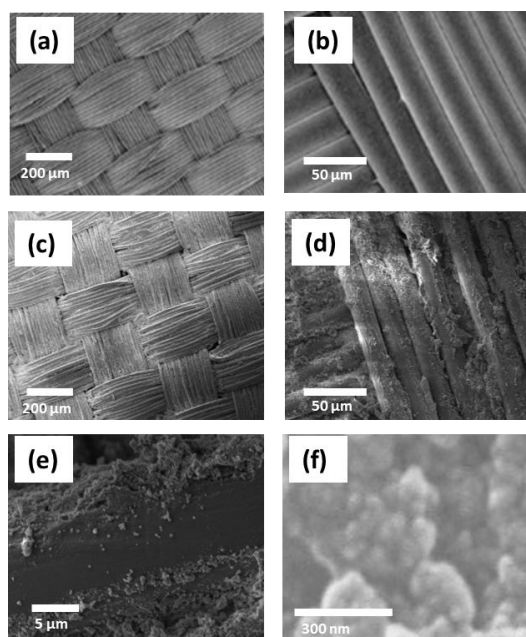


Figure 1: SEM images of PF before and after applying superhydrophobic coating: (a, b) Non-coated PF showing smooth, uniform fibers with minimal surface roughness; (c, d) Coated PF displaying increased roughness and hierarchical micro/nano-structuring; (e) Multilayer deposition of SiO₂ particles on coated PF at 5 μm scale; (f) Porous SiO₂ nano/micro-structured surface at 300 nm scale.

The superhydrophobic surface observed in this study was successfully developed through the synthesis of SiO₂ nanoparticles followed by surface modification with HDTMS. Initially, TEOS underwent hydrolysis and condensation reactions, resulting in the formation of SiO₂ nanoparticles. During this process, hydroxyl (-OH) groups on the untreated polyester fabric were replaced by siloxane (Si–O–Si) bonds, establishing strong chemical linkages with the fabric substrate. Subsequent modification with HDTMS introduced long-chain alkyl groups through further hydrolysis and condensation, forming

hydrophobic tails on the surface of the SiO₂ nanoparticles. These functionalized nanoparticles tended to aggregate into microclusters, creating a multilayered, porous nano-microstructured surface. This dual-scale surface structure not only enhanced the physical roughness of the coating but also contributed to more effective coverage of the remaining –OH groups. As a result, the surface exhibited significantly reduced wettability by preventing direct contact between water droplets and the fabric, while simultaneously trapping air within the porous matrix, both key features of superhydrophobic behavior (Sotoudeh *et al.*, 2023).

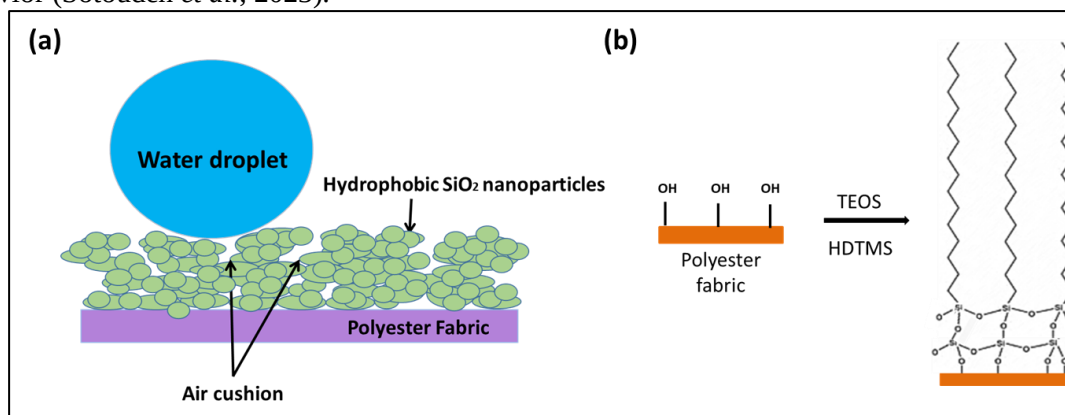


Figure 2: (a) Schematic illustration of the formation of the superhydrophobic coating on the PF surface (b) Chemical representation of the surface interactions between TEOS derived SiO₂ and HDTMS on the PF substrate, highlighting the formation of Si–O–Si bonds and the alignment of long-chain hydrophobic alkyl groups that contribute to the development of a water-repellent surface.

The EDX elemental mapping (Figure 3a) showed a uniform distribution of C, O, and Si on the coated fabric surface, confirming even coverage by the TEOS-HDTMS hybrid coating. The strong Si signal indicated a continuous silica network, while prominent C and O peaks (Figure 3b) suggested a high presence of hydrophobic –CH₃ groups from HDTMS. The FTIR analysis revealed the formation of new bonds on the PF surface following the application of the superhydrophobic coating, including Si–O–Si, Si–C, and Si–O (Cao *et al.*, 2023). Additionally, the intensity of these peaks increased compared to the untreated PF surface (Figure 3c), indicating the successful incorporation of similar functional groups from HDTMS (Xu and Zhang, 2021) (Figure 3d). Together, these results demonstrated the successful formation of a uniform, water-repellent surface via sol–gel treatment.

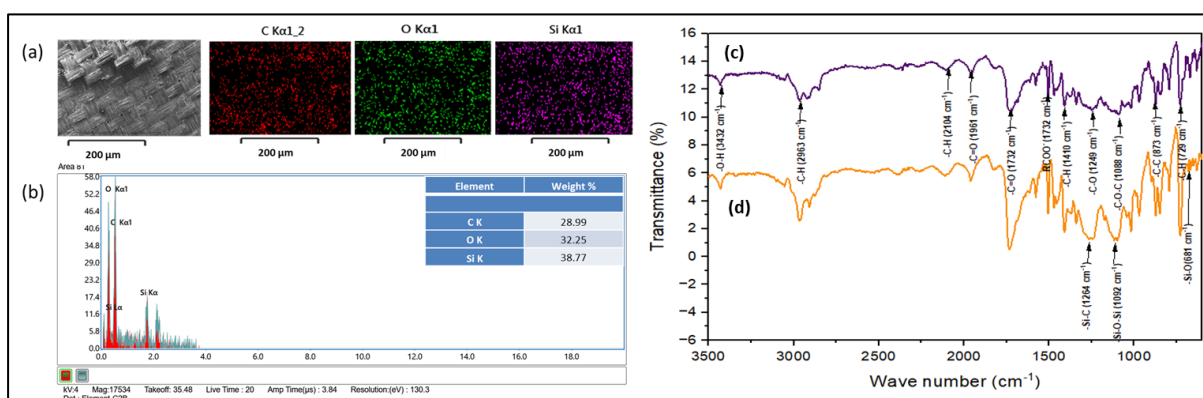


Figure 3: (a) EDX elemental mapping images, (b) EDX analysis and spectrum, (c) FTIR spectrum of non-treated PF, (d) FTIR spectrum of treated PF

The AFM analysis further exhibited the formation of a hierarchical surface architecture characterized by micro and nanoscale roughness (Figure 4a & b). The average surface roughness (Ra) of the untreated

fabric was measured at approximately 5 nm, whereas the coated fabric exhibited a significantly increased Ra of 25 nm. This substantial enhancement in surface roughness confirmed the successful creation of a dual-scale topography induced by the TEOS-HDTMS coating. Such dual-scale surface structure are known to play a critical role in promoting superhydrophobic behavior by effectively trapping air and minimizing solid–liquid contact, thus supporting the observed water-repellent properties of the treated fabric (Teisala *et al.*, 2012).

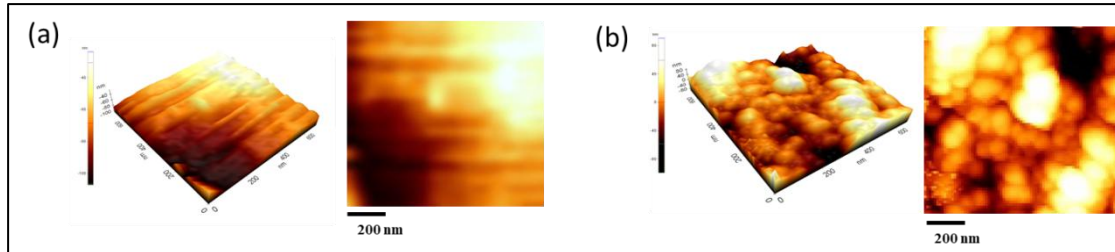


Figure 4: AFM images of (a) non-treated PF and (b) treated PF.

3.2 Wettability and Self-cleaning Ability

The treated fabric exhibited a high contact angle of $163^\circ \pm 2^\circ$ and a low sliding angle of 8° (Figure 5), signifying minimal droplet adhesion. This behavior is attributed to the micro-nano patterned structure formed by the coating, which traps air at the interface and promotes a Cassie–Baxter wetting state, thereby enhancing surface hydrophobicity.

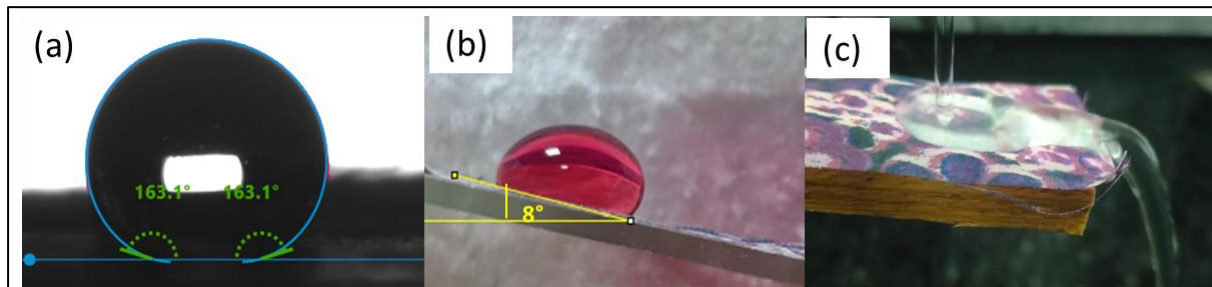


Figure 5: (a) Water contact angle of treated PF, (b) Sliding angle of treated PF, (c) Water roll off from the treated fabric surface

The self-cleaning ability of the superhydrophobic coating was demonstrated by applying mud to the treated PF, followed by rolling water droplets over the surface. As shown in Figure 6a, the droplets effectively removed the mud, illustrating the low adhesion between contaminants and the micro/nano-structured surface. This dual-scale roughness promotes high contact angles and droplet mobility, enabling efficient dirt removal without chemicals or scrubbing. Additionally, the coating maintained high water contact angles ($>150^\circ$) with various liquids, including tea, milk, malt, sauces, and dyes after 1 hour of exposure (Figure 6b), confirming its robust repellency and practical applicability.

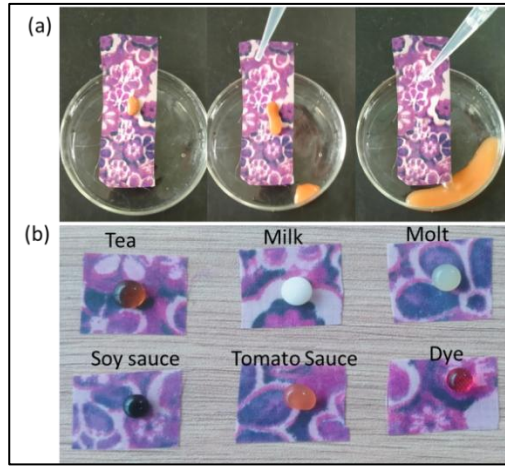


Figure 6: (a) Self-cleaning test for treated PF with mud, (b) Spherical droplet formation by different beverages, sause items and food dye on treated PF

3.3 Robustness and Durability

Tensile testing revealed that the superhydrophobic coating significantly enhanced the mechanical strength of PF, with tensile strength increasing from ~50 MPa to ~100 MPa post-treatment (Figure 7 a & b). The coated fabric also demonstrated excellent chemical durability, maintaining superhydrophobicity across a pH range of 5 to 11 (Figure 7c), despite potential corrosive effects on microstructured surfaces. Mechanical robustness was confirmed through abrasion testing; even after 150 abrasion cycles, the treated PF retained a water contact angle above 150° and remained dry upon immersion, indicating strong long-term water repellency and wear resistance (Figure 7d). Washing stability tests demonstrated that the coating sustained up to 40 minutes of continuous exposure to a 0.5 cm diameter water jet at a pressure of 100 kPa without exhibiting any visible signs of degradation (Figure 7e). This exceptional performance reflects the coating's superior adhesion and mechanical durability under simulated laundering conditions.

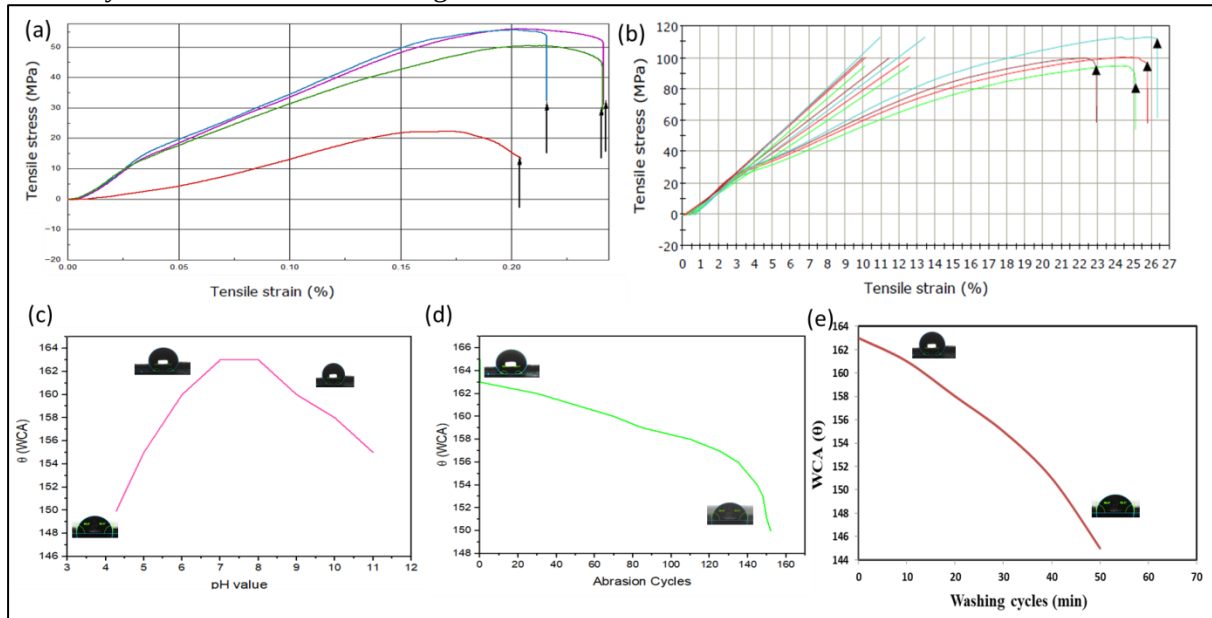


Figure 7: Tensile measurements of (a) non-treated PFs and (b) treated PFs, (c) variations in superhydrophobicity of treated PFs across different pH levels, (d) Graph of Water contact angles under different abrasion cycles, (e) Graph of washing stability

4. Conclusion

In conclusion, this research represents a significant advancement in the development of sustainable, high-performance materials for outdoor textile applications through the design of an eco-friendly superhydrophobic coating for polyester umbrella fabrics. Utilizing a simple and scalable sol–gel process with TEOS and HDTMS, the coating was applied via a sponge-assisted method, resulting in a distinctive multi-layered nano/microstructured surface composed of randomly distributed functionalized SiO₂ nanoparticles. This hierarchical surface architecture greatly enhanced surface roughness and air entrapment, leading to outstanding water-repellent performance, as evidenced by a high contact angle of $163^{\circ} \pm 2^{\circ}$ and a low sliding angle of 8° . In addition to superhydrophobicity, the treated fabric demonstrated a significant improvement in mechanical properties, including a 50 MPa increase in tensile strength and excellent abrasion resistance, maintaining functionality after 150 sandpaper cycles. Furthermore, the coating exhibited strong resistance to continuous water jet exposure at 100 kPa for up to 40 minutes, along with chemical stability across a broad pH range (5–11) and reliable self-cleaning ability against various common contaminants such as mud, sauces, and beverages. Collectively, these findings highlight the exceptional durability of the coating, mechanical integrity, and environmental compatibility, establishing it as a promising and practical solution for extending the functional lifespan of polyester fabrics in demanding outdoor conditions.

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