The Open University of Sri Lanka

Second International conference on circular economy and Sustainable Ecosystem 2025



Conference Proceedings

C²ESE
International Conference on Circular Economy and Sustainable Ecosystem



The Open University of Sri Lanka

Department of Mechanical Engineering

Proceedings

Second International Conference on Circular Economy and Sustainable Ecosystem

IC^{2}ESE 2025

11th December

Colombo, Sri Lanka

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ISSN 3093-6128

Message from the Vice Chancellor

Dear Delegates, Scholars, Industry Experts, and Esteemed Guests,



It is with great pleasure that I welcome you to the 2nd International Conference on Circular Economy and Sustainable Ecosystem (IC^2ESE 2025). This important event is organized by the Department of Mechanical Engineering of the Open University of Sri Lanka (OUSL), in collaboration with valued partners, Explore Energy Sweden (AB), AirMech (Pvt) Ltd, and several institutions committed to sustainability and climate action.

Last year, IC^2ESE 2024 was successfully held, with strong participation from local and international experts, and the positive outcomes and feedback inspired us to continue the conference this year with an even broader scope and ambition. This year's conference focuses on innovative and practical approaches that support the global shift towards a circular and environmentally resilient future. IC^2ESE 2025 brings together experts from academia, industry, and government to explore essential topics such as resource recovery, sustainable manufacturing, eco-design, waste minimization, renewable energy, and green technologies. The insights shared here will help strengthen collaboration between researchers and industry, creating pathways to real solutions that support national and global sustainability goals.

I am honored to participate as both the Vice Chancellor and the Chief Guest for this year's event. The Open University of Sri Lanka takes pride in fostering academic excellence and promoting research that addresses real-world challenges. This conference aligns strongly with our commitment to building knowledge, encouraging innovation, and supporting the country's journey towards a greener future.

I encourage all participants to engage actively, share their ideas, question traditional approaches, and build collaborations that continue beyond this event. Together, we can inspire impactful actions that will contribute to a more circular, efficient, and sustainable ecosystem.

I wish all of you a productive and meaningful conference. May IC^2ESE 2025 be a platform that sparks new thinking, strong partnerships, and practical strategies for a better tomorrow.

Warm regards,

Snr. Professor P M C Thilakarathne

Vice Chancellor

The Open University of Sri Lanka

Message from the Conference Chair



It is my great pleasure to welcome you to the second International Conference on Circular Economy and Sustainable Ecosystem, organized by the Department of Mechanical Engineering of the Open University of Sri Lanka. This year's theme, "Unlocking the Potential for Green Recovery," could not be more appropriate or urgent than ever. We gather once again at a time when the world is confronting social and economic challenges, largely driven by intensifying environmental degradation caused by human activities.

It was only a few days ago that Sri Lanka experienced severe and widespread flooding, displacing communities, damaging infrastructure, disrupting livelihoods, and reiterating the escalating consequences of climate change. These events have not only exposed our physical vulnerabilities but also highlighted the limitations of traditional, linear development models. The concept of a green recovery, intrinsically linked to the principles of the circular economy, offers a transformative framework for rebuilding economies that is robust, regenerative, and equitable. The circular-economy approach, based on principles of resource efficiency, waste minimization, reuse, renewal, and ecological balance, offers a realistic and compelling framework for rebuilding societies in ways that are both economically sound and environmentally responsible. A "green recovery" is not merely an aspiration; it is a pathway to strengthening national and regional resilience. It calls for rethinking production processes, redesigning supply chains, diversifying energy systems, restoring ecosystems, and embracing technological innovation. Moreover, it encourages inclusive, equitable development, ensuring that communities are not only protected from future environmental shocks but are also empowered to thrive within a regenerative and sustainable economic system. As we recover from various global disruptions, the importance of a green recovery is stronger than ever. It is not merely about restoring what was lost but about building a better, more resilient, and truly sustainable future.

This conference provides a vital platform for these conversations. The research presented, the discussions initiated, and the collaborations formed here will directly contribute to shaping policies and practices that guide our transition toward a resilient and sustainable future. At the time I write this note for the conference proceedings, I encourage each participant to engage actively, question boldly, and contribute meaningfully to broaden the horizons of knowledge and innovation. I extend my sincere gratitude to our keynote speakers, authors, reviewers, session chairs, organizing committee members, and all participants whose dedication has made this conference possible. Your commitment to advancing the principles of circularity and sustainability brings us closer to the vision of a greener, more secure, and more prosperous world.

I wish you all a productive, inspiring, and fulfilling conference experience.

Dr. S. D. R. Perera,

Conference Chair,

Senior Lecturer

Department of Mechanical Engineering

Message from the Conference Secretary



It is a great privilege and pleasure to welcome all participants warmly, distinguished keynote speakers, researchers, academicians, industry professionals, and students to the International Conference on Circular Economy and Sustainable Ecosystem (IC²ESE 2025), hosted by the Mechanical Engineering Department of the Faculty of Engineering Technology, The Open University of Sri Lanka. We are truly honored to host this important international gathering dedicated to advancing sustainability and circular innovation.

IC²ESE 2025 is guided by the inspiring theme, "Transformative Circular Solutions for a Regenerative and Resilient World." This theme reflects the urgent global demand for sustainable development, responsible resource use, innovative energy solutions, and circular economic practices. This international conference brings together diverse expertise across key thematic tracks, creating a multidisciplinary platform that links academic research, industry practices, and policy development.

Beyond being a forum for academic exchange, IC²ESE 2025 aims to strengthen professional networks, inspire young researchers, and encourage innovative thinking that translates knowledge into real-world impact. We strongly encourage all participants to actively engage in discussions, initiate collaborations across disciplines and borders, and explore opportunities for research, entrepreneurship, and sustainable industrial transformation.

As the Secretary of IC²ESE 2025, I extend my sincere appreciation and heartfelt gratitude to all individuals and institutions whose dedication, commitment, and invaluable contributions have made this prestigious conference a reality. Your continued support and cooperation are the true pillars of this event's success.

I believe that IC²ESE 2025 will be an intellectually stimulating and professionally fulfilling experience for everyone. May this conference inspire innovative ideas, responsible innovation, and enduring collaborations.

Wishing you a productive conference and an enriching experience.

With best wishes,

Dr. B.G.D. Achintha Madhusanka

Secretary – IC²ESE 2025

International Conference on Circular Economy and Sustainable Ecosystem

Department of Mechanical Engineering

The Open University of Sri Lanka

Message from the Conference Coordinator



It is with great pleasure that I welcome you all to the International Conference on Circular Economy and Sustainable Ecosystem (IC2ESE 2025). As the Conference Coordinator and Head of the Department of Mechanical Engineering at The Open University of Sri Lanka, I am honoured to continue supporting this important international event. Following the success of IC2ESE 2024, this year's conference builds further on our shared commitment to sustainability, innovation, and knowledge exchange. The discussions and outcomes from last year clearly showed the growing global interest in circular economy practices and ecosystem resilience. This year, we look forward to strengthening that momentum and expanding the impact of our collective efforts.

IC2ESE 2025 provides a valuable platform for researchers, practitioners, industry leaders, and policymakers to come together and explore practical pathways toward a more sustainable future. Through presentations, keynote sessions, and networking opportunities, the conference aims to foster collaboration and inspire new ideas aligned with both national and global sustainability goals. The Department of Mechanical Engineering, together with our local and international partners, is committed to ensuring a high-quality academic and professional experience for all participants. I sincerely appreciate the contribution of every committee member, speaker, reviewer, and sponsor who has supported this year's event.

I encourage all attendees to make the most of the conference sessions, share their insights, and connect with fellow participants. Your active engagement will help us move closer to effective solutions that support circular economic transitions and sustainable ecosystem development. I wish you a meaningful, productive, and inspiring experience at IC2ESE 2025.

Warm regards,

Eng. H.D.N.S. Priyankara, Conference Coordinator

Senior Lecturer / Head, Department of Mechanical Engineering

The Open University of Sri Lanka

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Circular Economy in Sri Lankan Construction: Awareness, Practices, and Implementation Barriers

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Abstract: The construction sector consumes vast quantities of virgin resources, generates 40% of global solid waste, and contributes 11% of energy-related CO_2 emissions. Circular Economy (CE) principles offer a cradle-to-cradle alternative that can decouple growth from resource depletion. However, empirical knowledge of CE adoption in emerging economies remains limited. This study used questionnaire surveys followed by semi-structured interviews to examine CE awareness, current practices, barriers, and enablers in Sri Lanka's construction industry. An online questionnaire (N = 86) targeting contractors, consultants, architects, clients, policymakers, and sustainability advocates was complemented by semi-structured interviews with sector leaders. Quantitative analysis (descriptive statistics, Pearson's r) revealed that adopting a circular business model, prioritizing environmental protection, and recognizing its benefits will encourage the adoption of CE principles. Conversely, perceived financial incentives were weakly correlated with adoption intent (r = .04). Approximately 19.8% of policymakers/advocates, 12.5% of clients, 10.72% of contractors, and 7.23% of architects lacked basic CE literacy. Qualitative findings highlighted outdated regulations, insufficient R&D, limited reverse logistics infrastructure, and low market demand for recycled materials, which discourage the implementation of CE concepts in the Sri Lankan construction industry. Drawing on global best practice and theory, a stakeholder-driven implementation is proposed that prioritizes (1) regulatory modernization, (2) fiscal and market incentives for circular business models, (3) professional and public education, and (4) collaborative data-sharing platforms. The study delineates concrete responsibilities for government, industry, academia, and waste processors to accelerate Sri Lanka's transition from a linear to circular construction paradigm.

Keywords: Circular Economy, Construction Industry of Sri Lanka, Built environment

1 Introduction

Linear "take-make-dispose" models have made the construction sector the world's largest consumer of raw materials and source of solid waste [1]. This linear model is no longer viable given rapid population growth and rising material demands. The construction industry alone accounts for nearly 33% of annual material consumption [2]. Global trends are increasingly shifting toward Circular Economy (CE) principles to address these challenges. CE prioritizes resource efficiency, waste minimization, and lifecycle management [3].

CE aims to regenerate, share, optimize, loop, virtualize, and exchange resources within the built environment. Frameworks such as ReSOLVE, developed by the Ellen MacArthur Foundation, guide these processes [4]. In Sri Lanka, the concept of circularity in the construction industry remains relatively new and requires greater attention [5]. Some CE practices, such as the Construction Waste Management (COWAM) program, are underway. This initiative recycles waste into products like interlocking blocks and aggregate for road construction [6].

Sri Lanka continues to struggle with inefficient material use and inadequate waste management. Much of the construction waste is in landfills or illegal dumps [7]. Local studies show the urgent need for government-led policies, stakeholder engagement, and adoption of eco-friendly waste management systems [7]. Recent research also emphasizes the need for comprehensive frameworks tailored to national conditions. Persistent barriers include limited technical know-how, weak regulatory enforcement, and insufficient market incentives [8]. Based on these gaps, this research sets out three main objectives:

1. To quantify awareness and current practices of CE within Sri Lanka's construction sector.
2. To identify key barriers and drivers for implementing CE principles.

2 Literature Review

The construction industry accounts for approximately 40% of global resource consumption and 39% of carbon emissions, underscoring the critical role of CE principles in achieving sustainability goals [9]. CE in construction

represents a paradigm shift from the traditional linear "take-make-dispose" model to a regenerative system emphasizing resource efficiency and waste elimination. The concept includes multiple R-strategies, and recent frameworks incorporate up to 10 R principles: refuse, reduce, reuse, repurpose, refurbish, remanufacture, recycle, recover, and regenerate [10]. These strategies aim to slow, close, and narrow resource loops while maintaining materials at their highest value throughout building lifecycles.

High upfront investment costs are the most significant barrier to implementing CE across multiple studies. Construction stakeholders frequently resist CE adoption due to immediate cost implications, despite long-term economic benefits [11]. The lack of established markets for recycled materials and the absence of economic incentives further compound financial challenges [11].

Educational barriers account for 18% of the identified impediments to CE implementation. Studies reveal substantial knowledge gaps among construction professionals, with architects (7.23%), contractors (10.72%), and legislative policymakers (19.81%) demonstrating limited understanding of CE concepts [12]. Regulatory frameworks remain inadequate for supporting CE implementation. Policy inconsistencies between regions create additional implementation challenges [11]. Technical barriers account for 29% of the identified challenges, including limited infrastructure for material recovery and processing [13]. Design-related obstacles include conflicts between pre-engineered structures and future reuse requirements, a lack of standardization in building components, and insufficient technologies for CE-based material recycling. The complexity of composite materials prevents effective end-of-life material separation [13].

Effective policy frameworks are a key driver, with studies emphasizing the need for updated regulations to support material reuse and recycling [14]. Green public procurement policies and fiscal incentives, such as tax reductions for sustainable materials, demonstrate significant potential to accelerate CE adoption [15]. Enhanced education and training programs represent fundamental enablers for CE implementation [14]. Research indicates the need to integrate CE concepts into academic and professional development frameworks [16]. Stakeholder awareness campaigns and demonstration projects can effectively bridge knowledge gaps.

Developing appropriate technologies for material recovery and recycling is another driver for CE implementation [14]. Digital tools facilitate CE implementation, including the integration of Building Information Modeling (BIM) and the use of material passports. These tools enable better tracking and management of resources throughout building lifecycles [17]. Standardization of recycled materials and components is also an essential enabler [18].

Circular business models and financial incentives strongly correlate with CE adoption, with studies reporting positive associations of 23.4% and 22.3%, respectively [19]. Easy wins from improved business cases correlate with willingness to adopt at 23.3% [19]. The current literature shows limited empirical research on CE implementation across geographic contexts [20]. Standardized metrics for measuring circularity performance remain underdeveloped [21]. Future research should focus on developing quantitative assessment frameworks and conducting longitudinal studies to evaluate the long-term impacts of CE interventions [22]. This comprehensive approach is essential for advancing CE adoption and achieving sustainability objectives in the built environment.

3 Methodology

The research project employs a mixed-method approach to assess circular economy (CE) practices, awareness, and barriers within Sri Lanka's construction industry. The process was divided into quantitative surveys, data analysis, and targeted qualitative interviews to enhance robustness.

3.1 Survey Development and Execution

A comprehensive questionnaire was developed to evaluate CE awareness and ongoing practices quantitatively. A 4-point Likert scale (1 = lowest, 4 = highest) was used for precise measurement. Critical revisions were made after the pilot survey, involving an initial sample of five industry professionals. The questionnaire was distributed among 150 industry stakeholders for 4 weeks. Respondents represented a spectrum of industry stakeholders, including association members, consultants, manufacturers, contractors, and owners. These stakeholders were selected via the CIDA database and governmental sources. The survey was distributed via Microsoft Forms, which includes translation and audio support. At the end of the survey, 93 responses were collected for data analysis.

The survey consists of 54 questions spanning eight thematic domains: participant profile, CE principles, current practices, cultural, regulatory, financial, and sectoral barriers/enablers, and prospects for CE in construction.

3.2 Data Analysis Procedures

Rigorous data validation excluded inconsistent entries (based on completion time, IP, and response patterns), yielding 86 valid responses. Quantitative analyses employed the mean, standard deviation, and Pearson's r correlation. Thematic grouping clearly visualized awareness levels, prevailing practices, implementation barriers, and drivers.

3.3 Structured Interview Design and Execution

The survey insights directly informed us in the development of a detailed interview. Topics explored included organizational initiatives, promotion methods, integrative platforms, policy reform, fiscal support, producer responsibility, and data-sharing frameworks within the industry. Two expert practitioners, an architect/sustainability consultant and an architectural technologist, were selected from survey respondents for in-depth, virtual or phone interviews to provide qualitative elucidation.

3.4 Results Compilation

Quantitative and qualitative data were synthesized into a multi-stakeholder categorization. This aligns sector-specific recommendations with broader institutional and policy strategies, contributing a pragmatic roadmap for CE implementation.

4 Results and Discussion

4.1 Awareness and Practice Levels

Survey findings reveal substantial variation in CE awareness across stakeholder groups. Legislative policymakers (19.8%), clients (12.5%), and contractors (10.7%) exhibit the most significant knowledge gaps. This shows that foundational concepts of circularity remain poorly disseminated among those most critical for sectoral transformation. While most respondents acknowledged the environmental and resource-efficiency benefits that CE could confer, practical application in Sri Lanka's construction sector remains limited. This mirrors regional trends, where technological platforms for circular material reuse, recycling, and recovery are often unavailable or underused, as evidenced by limited research and a lack of robust case studies on local CE integration.

Ratings among construction professionals, policy makers, and clients for CE research sufficiency, technology availability, and operational practice cluster at insufficient levels (2.0–2.4 on the Likert scale). Engagement in cross-industry collaboration and on-site waste-sorting protocols is also low, with public CE awareness and the adoption of circular business models as critical weaknesses. Slightly higher scores for market development around recycled products point to early yet uneven ecosystem emergence.

All groups reported low-to-moderate engagement in cross-industry collaboration for circularity (2.2–2.4) and minimal implementation of on-site waste-sorting protocols (1.7–2.0). Severe deficiencies in public awareness (1.1–1.2) and limited adoption of circular business models (1.3–1.5) are evident. Figure 3: "Stakeholder Ratings for Collaboration, Practice, and Awareness" will compare ratings for these operational dimensions and business model adoption across all respondent categories.

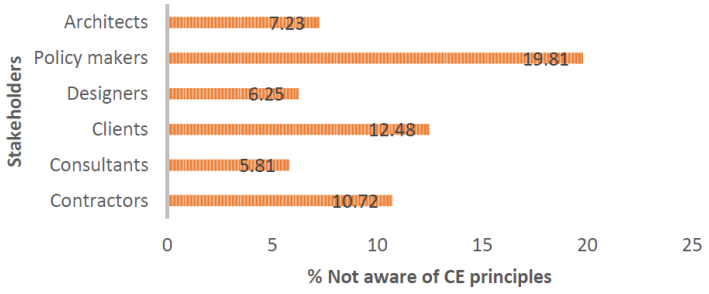


Fig. 1 Stakeholder CE Awareness Gap

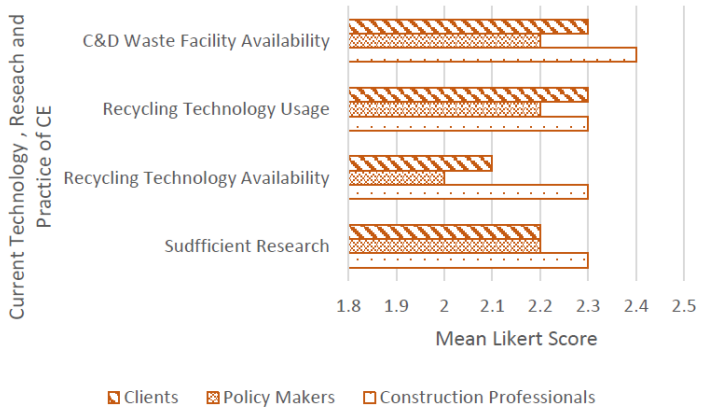


Fig. 2 Mean Likert Scores for CE Research, Technology, and Practice

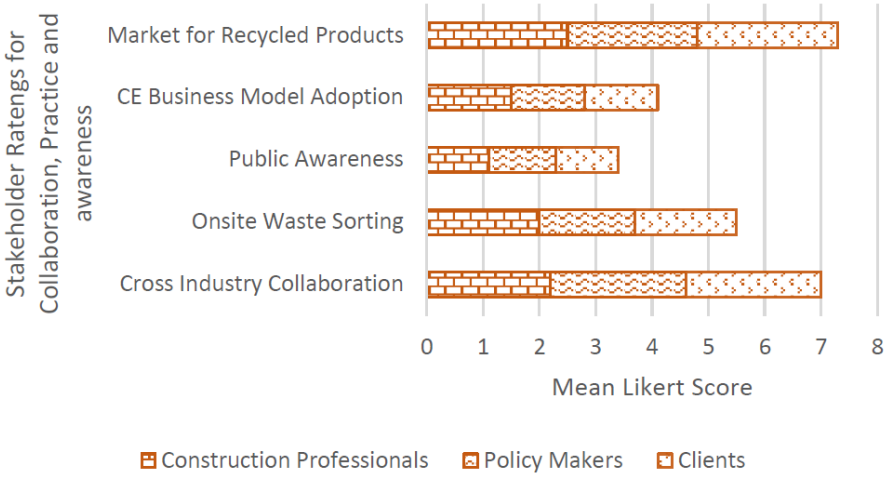


Fig. 3 Stakeholder Ratings for Collaboration, Practice, and Awareness

As measured by stakeholder perceptions, the market for recycled products receives slightly higher ratings (2.3–2.5), indicating an emerging yet incomplete ecosystem supporting circular construction outputs.

4.2 Barrier and Driver Identification

Significant barriers identified by survey respondents include outdated regulatory frameworks, insufficient fiscal support, fragmented collaboration along the value chain, and a cultural preference for conventional linear practices. Construction waste is predominantly disposed of in landfills, with divergent stakeholder understanding of legal versus illegal protocols. Underdeveloped market and incentive structures deter robust circular engagement, while professional planning and design tools for CE are rarely integrated. Figure 4: "Barriers and Supports for CE Implementation" visualizes stakeholder ratings of the sufficiency of policies and financial support, as well as the perceived impact of high upfront costs. Such evidence will highlight the comparative intensity of these challenges among different groups.

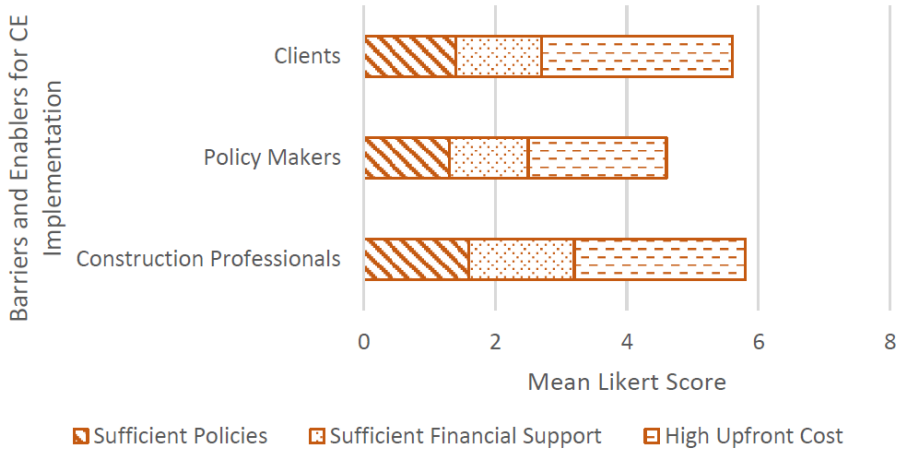


Fig. 4 Barriers and Supports for CE Implementation

The growing markets for recycled products (2.3–2.5) and technological infrastructure suggest incremental progress, contingent on advancement in policy, fiscal, and educational sectors.

Correlation analysis indicates drivers of CE adoption intent. The business-case strength for circularity (Pearson r = 0.233), Circular Business Models (CBM, r = 0.234), and energy/water conservation strategies (r = 0.223) is substantial. At the same time, financial incentives exert a notably weaker effect (r = 0.04). Figure 5 illustrates the relative influence of drivers, including CBM, environmental practices, and economic incentives, on stakeholder adoption intent.



Fig. 5 Drivers of CE Adoption: Correlation Coefficients

Holistically, quantitative and qualitative strands of evidence highlight persistent deficits in knowledge, policy coherence, financial support, and collaboration. While nascent markets and platforms exist, systemic constraints, regulatory inertia, weak demand, fragmented education, and underdeveloped integration limit the effectiveness of

sectoral transition. Stakeholder-driven reforms, encompassing regulatory modernization, targeted fiscal and market incentives, and layered capacity-building, remain prerequisites for the evolution of a circular construction paradigm in Sri Lanka.

5 Conclusion

This study reveals that awareness, practices, and enabling conditions for Circular Economy (CE) implementation in Sri Lanka's construction industry remain incipient, with persistent systemic barriers impeding progress. Quantitative analysis across key stakeholder groups, construction professionals, policy makers, and clients, demonstrates insufficient knowledge of CE principles, limited availability and use of recycling technologies, and poor market development for recycled products. Ratings for public awareness and institutional support are notably low. At the same time, perceived barriers, such as high upfront costs and a lack of policy and financial incentives, are substantial across all respondents.

Significantly, the weakest correlations with CE adoption intent were associated with financial incentives, whereas circular business models, demonstrable business cases, "easy wins," and environmental protection imperatives exhibited stronger associations. These findings show misalignment between current incentive structures and the practical drivers required to accelerate CE uptake. Qualitative insights further indicate challenges posed by outdated regulations, inadequate R&D and reverse logistics, and fragmented stakeholder education, all of which hinder effective sectoral transformation.

These indicate the need to prioritize regulatory updates, targeted fiscal and market support, professional and public education, and comprehensive stakeholder collaboration to advance data sharing, innovation, and circularity. Implementing these is essential for Sri Lanka's transition from a linear, resource-intensive construction paradigm to one grounded in circular principles, sustainable resource management, and environmental accountability.

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A Knowledge Integration Methodology for Co-Creating Sustainable Solutions

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Abstract. Traditional top-down approaches to technology adoption in development cooperation often prove unsustainable, as externally designed solutions fail to align with local realities. This paper details Knowledge Integration Actions, a robust, co-creative framework that reframes this process by positioning local actors as protagonists. Validated through pilot actions with indigenous communities and entrepreneurs in Colombia and Bolivia, the methodology facilitates a just and effective adoption of technology through a bidirectional knowledge transfer. While external technical experts serve as facilitators, participants retain full ownership of the analysis and solution design, enabling genuine appropriation of culturally pertinent, self-managed solutions.

The framework is highly flexible and has been successfully applied in two distinct modalities. The first guides community groups in designing energy solutions. The second empowers entrepreneurs to develop concrete action plans for their businesses. Pilot actions have focused on thematic areas such as renewable energy, tackling energy poverty, and improving the value chains of local products, including artisan handicrafts and food production. In these actions, participants move from diagnosing their current processes and challenges to creating structured, realistic improvement plans, often integrating digital tools for marketing and research.

Energy-focused actions, for instance, have enabled communities to co-design not only their own renewable systems, such as solar microgrids, but also the crucial management and maintenance models required for long-term success. Entrepreneurship activities guide individuals in creating detailed business improvement plans and foster innovation in products and processes. By building technical and managerial autonomy and deliberately strengthening women's leadership, this model provides a transformative pathway to the sustainable adoption of technology, generating just and resilient local development.

Keywords: Knowledge Integration, Co-creation, Participatory Design, Entrepreneurship, Sustainable Energy.

1 Introduction

The incorporation of technology and management improvements in vulnerable communities is a cornerstone of development cooperation. Despite substantial investment, these initiatives frequently fail to achieve sustainable results. A recurrent cause of this failure is the prevalence of traditional top-down approaches, in which externally designed solutions are imposed on communities without sufficient regard for their specific contexts. Too often, these external solutions fail to take root because they do not align with local realities, cultural aspirations, or the population's existing knowledge base. Consequently, when external funding or technical support is withdrawn, the implemented technologies or processes are often abandoned, having failed to generate genuine appropriation among the intended beneficiaries.

To address this persistent challenge, this paper proposes a paradigm shift through a framework defined as "Knowledge Integration Actions". This approach is born of the conviction that sustainable development is only possible when communities transition from passive recipients of aid to protagonists of their own improvement. In this model, the most powerful and lasting innovation arises from the very heart of the community, combining valuable local knowledge with external tools and methodologies.

The concept of Knowledge Integration, as used here, rests on the premise that knowledge is jointly constructed. It rejects the hierarchy where external experts dictate solutions. Instead, it establishes a bidirectional transfer of knowledge. External technicians and experts participate not as directors, but as facilitators and catalysts. Their role is to provide access to information, technical training, and structured methodologies, such as business model analysis or

technical system design, that allow the community to structure their own process of discovery and creation. Simultaneously, the community contributes its deep understanding of the environment, social dynamics, and specific needs, assets that are essential for building relevant solutions.

This paper details the methodology and results of this framework, which was validated through pilot actions conducted in two distinct geographic and cultural contexts: indigenous Wayúu communities in La Guajira, Colombia, and women entrepreneurs in the Valle Alto region of Cochabamba, Bolivia. These interventions covered diverse thematic areas, ranging from the co-creation of alternative energy systems and the optimization of artisan production processes in Colombia to innovation in entrepreneurship plans in Bolivia.

The following sections will detail the theoretical underpinnings of this participatory design approach, the specific methodological steps applied in the workshops, and the results obtained. By recognizing the value of local knowledge and promoting autonomy, this model seeks to demonstrate that vulnerable communities can shape their own technological and economic future, ensuring that solutions are not only effective but also culturally relevant and resilient over time.

2 Theoretical Framework

To understand the necessity and mechanics of Knowledge Integration Actions, one must first critically analyze the historical failures of technology transfer in development contexts and, secondly, define the epistemological value of local knowledge. This section outlines the theoretical transition from a deficit thinking model of development to a model of hybridity and co-creation, supported by recent scholarship in indigenous education and poverty research.

2.1 Beyond the Deficit Thinking Model: Re-evaluating Technology Transfer

Historically, development interventions and educational programs targeting indigenous and vulnerable communities have been predicated on a deficit thinking model [1]. This approach assumes that these communities lack the necessary knowledge, technology, or capacity to manage their own development, thereby justifying a top-down imposition of external solutions. As noted by scholars in the field of indigenous poverty, this perspective frequently misdiagnoses the problem. Poverty is a multidimensional phenomenon related to the imposition of the dominant group's culture, racism, and social marginalization [2].

In the context of technology adoption, whether it be renewable energy infrastructure, digital management tools for businesses, or other technologies, the deficit-thinking model often manifests as a form of technological imposition. Western science and technology are presented as the only valid epistemologies, implicitly rendering indigenous or local knowledge systems as primitive or irrelevant. Gumbo and Williams [3] argue that contextualizing the technology curriculum requires acknowledging that indigenous communities have always possessed sophisticated technological knowledge systems. Indigenous solutions would provide effective responses to local contexts, causing less harm to the natural environment by respecting the tripartite relationship among humans, spirituality, and nature [3]. Therefore, interventions that ignore these pre-existing systems are destined to fail, as they produce culturally dissonant solutions that lack local ownership.

2.2 Traditional Knowledge Systems (TKS) and Contextual Learning

Traditional knowledge systems (TKS) consist of interconnected knowledge, practices, and beliefs that have evolved over generations within specific communities and are deeply rooted in their cultural, social, and environmental contexts. They span domains such as agriculture, medicine, and resource management, providing invaluable insights into sustainable practices. There is growing recognition of the importance of integrating TKS into development cooperation initiatives to foster resilience, cultural diversity, and sustainable development.

Integrating TKS into development cooperation allows for a more holistic understanding of local environments and social structures. Abdallah discusses how integrating indigenous knowledge systems with Western scientific paradigms can enhance the effectiveness of sustainable development efforts by offering culturally sensitive tools and approaches that resonate with local contexts [5]. Similarly, Dei emphasizes that ensuring development policies are socially inclusive and culturally aligned significantly improves cooperation between indigenous communities and external organizations, promoting collaborative decision-making and adaptive capacities [6]. Berkes et al. also highlight the rediscovery of traditional ecological knowledge, enabling communities to develop adaptive management strategies that respond to environmental change [7].

To bridge the gap between traditional ways of knowing and technical training, our methodology adopts a Contextual Learning framework, grounded in the theory that learning is most effective when situated within the learner's cultural and physical environment. In this view, true understanding arises not from isolated facts, but from direct engagement with the specific realities and challenges of one's environment. The Contextual Learning approach has proved effective for adopting new technologies in vulnerable communities [8].

In the pilot experiences presented in this paper, situating the workshops within the participants' territories to address immediate needs such as water scarcity or local market access validates their existing knowledge bases while introducing external tools as complementary resources rather than replacements. Consequently, the role of the external expert shifts from "instructor" to "facilitator," whose task is not to replace local knowledge but to dialogue with it, creating a bridge between technical specifications and the community's social organization and priorities.

3 Knowledge Integration Actions methodology

The Knowledge Integration Actions framework is designed as a flexible, participatory itinerary that guides communities from diagnosing their current reality to defining concrete implementation plans. The methodology relies on a bidirectional transfer of knowledge: external experts provide structure, technical tools, and facilitation, while local participants contribute their contextual knowledge, cultural priorities, and operational experience.

The methodology adapts to the specific topic addressed. In this study, we present its application in two distinct fields: Renewable Energy and Entrepreneurship and Innovation.

3.1 General Process and Tools

In both thematic areas, the methodology follows a four-phase structure. To ensure accessibility across diverse educational levels and languages (Wayúunaiki, Quechua, and Spanish), the process relies heavily on visual tools, such as murals, sticky notes, and diagrams, and on small working groups facilitated by bilingual local facilitators.

The phases of the activity are the following:

1. Diagnosis: Participants map their current situation (energy uses or business processes) using structured templates.
2. Knowledge Exchange: Facilitators introduce technical concepts (e.g., solar vs. wind technologies, or cost calculation methods) adapted to the local context.
3. Co-design and Prioritization: Participants identify challenges and match them with potential solutions, prioritizing those that align with their cultural values and long-term aspirations.
4. Action Planning: The process culminates in the creation of a detailed implementation plan (technical designs or business improvement plans).

3.2 Tools for Renewable Energy Actions

These actions aim to empower communities to lead the assessment, planning, and implementation of renewable energy solutions that align with their cultural values, lifestyles, and existing infrastructure. The methodology focuses on aligning technical possibilities with the community's social structure and includes the following activities:

- Needs Assessment Surveys: Before the workshop, participants conduct surveys in their own communities. These surveys are structured to gather data on current energy use in the home and community, community priorities, and productive energy needs (e.g., schools, water pumps).
- Infrastructure Mapping: Participants draw maps of their territories to identify existing resources (e.g., old windmills, community centers) and optimal locations for new systems.
- Technology Evaluation: Through facilitated debate, communities evaluate technologies (solar, wind, diesel) not just on technical metrics, but on compatibility with their lifestyle and maintenance capabilities.
- Management Model Co-design: A critical component is defining the governance model. Participants use a structured board to answer key questions, such as "Who owns the equipment?" Who pays for repairs? Who performs daily maintenance?

3.3 Tools for Entrepreneurship and Innovation Actions

This application focuses on empowering individual business owners or family units. It uses tools adapted from standard business management but simplified and translated into local contexts, and includes:

- A Business Map: This tool allows participants to visualize their entire production chain. For every step (e.g., "buying wool," "weaving," "selling"), they list the resources used, the time invested, and the people involved. This helps identify hidden costs and bottlenecks.
- Challenges vs. Dreams: Participants identify specific bottlenecks (e.g., rising cost of inputs, lack of transport) and contrast them with a "Dream" exercise, visualizing their business in one year.
- Strategic Focusing (Canvas): Using a "Canvas" scheme adapted for the context, entrepreneurs analyze value propositions and customer segments.
- Improvement Plans: The final output is a concrete action plan detailing the steps, resources, and deadlines for implementing the chosen improvement.

4 Workshops

The methodology described above was implemented in three workshops: one focused on Energy in Colombia and two on Entrepreneurship. This section details the execution and specific activities undertaken in each case.

4.1 Co-creation of Alternative Energy Systems (La Guajira, Colombia)

This workshop was held at the University of La Guajira with 25 participants (18 women, 6 men) from various Wayúu communities, including Albania, Amasirrary, and Jiyupure1. The objective was to co-design rural electrification systems that respected Wayúu customs while providing reliable energy [9].

The action was structured over three days, moving from diagnosis to technical design and management planning. Table 1 details the schedule followed, while the results of the activities for each day are presented in the subsections that follow.

The first day focused on diagnosing the current situation. A key activity was the Needs Assessment. Using previously conducted surveys, participants worked in groups to categorize energy use based on community consensus. The results of this prioritization were revealing. The groups unanimously prioritized "Very Important" communal uses related to survival and basic rights, specifically water pumping (essential in the arid Guajira region), refrigeration for health centers (medicines/vaccines), and night lighting for security to prevent livestock theft. Conversely, domestic ventilation (fans) and home lighting were categorized as "Important" but secondary to community survival, while productive machinery and large household appliances were categorized as "Less Priority".

Day 1. Diagnosis and Infrastructure.

Afterward, the participants conducted an Infrastructure Mapping exercise. They drew detailed maps of their communities, locating existing housing, schools, and energy installations. This revealed significant disparities; while some communities had existing (often non-functional) infrastructure, others had none. This visual exercise helped ground the technical discussion in the territory's physical reality.

Table 1. Activities and schedule of the action.

Time	Day 1	Day 2	Day 3
9:00 - 10:00 AM	Welcome and introductions	Technical design: collaborative design	Choice priorities: collaborative design
10:00 - 12:00 PM	Assessment of the community's energy needs	Technical design: feedback and refinement	Choice priorities: feedback and refinement
12:00 - 1:00 PM	Lunch break	Lunch break	Lunch break

1:00 - 3:00 PM	Assessment of existing infrastructure and interactive mapping	Management and maintenance: collaborative design	Project implementation: training and action planning
3:00 - 3:30 PM	Rest	Rest	Rest
3:30 - 5:00 PM	Examples of practical cases	Management and maintenance: feedback and refinement	Closing Ceremony

Day 2. Technical and Management Model Co-design.

The second day introduced the technical dimension, but the most critical activity was co-designing the management model. Participants addressed specific governance questions using sticky notes on a large mural. They successfully defined a tiered responsibility model. They determined that the community should be responsible for basic operation (e.g., cleaning solar panels) and administrative management to ensure daily functionality. However, they explicitly stated that complex technical repairs must be handled by specialized external technicians, recognizing their own limitations. Regarding finance, they agreed that while external entities (NGOs, government) should fund the initial investment, the community must contribute to operation and maintenance costs to ensure ownership.

Day 3. Planning of project implementation

On the final day, the participants defined exactly what training was needed for the project's success. They specified that, before implementation, the community needs training on the general scope; during installation, beneficiaries should be trained on operation; and, critically, they requested manuals, guides, and videos in their local language. Finally, a review of the main outcomes and conclusions was conducted.

4.2 Strengthening Wayúu Artisans (La Guajira, Colombia)

This action involved 32 women artisans from the Majalí community. The focus was on optimizing their production processes and exploring new commercial channels for their handicrafts (backpacks, chinchorros, and mantas) [10].

The workshop followed a rigorous itinerary designed to professionalize their trade without losing its cultural essence. The activities are detailed in Table 2.

Table 2. Activities and schedules of the action

Time	Day 1	Day 2	Day 3
09:00 - 10:00	Welcome and Introductions	Workshop 4: Work Organization and Productivity	Workshop 8: Making Informed Decisions
10:00 - 12:00	Workshop 1: Identifying Business Opportunities	Workshop 5: Inventory Management	Workshop 9: Action Planning: Tools
12:00 - 13:00	Lunch Break	Lunch Break	Lunch Break
13:00 - 15:00	Workshop 2: Basic Strategic Planning	Workshop 6: Basic Financial Control	Workshop 10: Action Planning: results
15:00 - 15:30	Break (Traditional snacks and drinks)	Break (Traditional snacks and drinks)	Break (Traditional snacks and drinks)

15:30 - 17:00	Workshop 3: Supply and Supplier Management	Workshop 7: Data Collection and Analysis	Workshop 11: Accessing Resources and Financing & Promoting Local Products & Closing Ceremony

The workshop began with the formation of working groups, which chose names such as "Orb-weaving spiders," "Ancestral essence," and "Weaving dreams." They listed their current products, which included backpacks, keychains, chinchorros (hammocks), and mantas. The groups then defined their primary interests for the workshop. Orb-weaving spiders focused on learning new designs and negotiation skills; Ancestral essence was interested in combining traditional techniques with modern designs and fair trade, while Weaving traditions focused on selling backpacks in new markets (outside Riohacha) for higher prices.

A pivotal activity was the detailed Cost Analysis. Participants calculated the "net income per hour worked" for different products. They broke down the material costs (threads, needles) and the time spent. The analysis revealed that a standard "Medium Backpack" took 12 hours to make and yielded a net income of only 667 Colombian Pesos (COP) per hour. In contrast, a "Large Backpack," which took 35 hours but commanded a much higher price, yielded 2,286 COP per hour. Table 3 presents a summary of these findings, which were revelatory for the artisans.

Table 3. Calculation of net income per hour for certain products

Product	Large backpack	Medium backpack 1	Medium backpack 2	Small backpack
Gross income[1]	$150,000	$35,000	$20,000	$10,000
Material units	20	10	5	3
Material unit cost	$2,000	$2,000	$2,000	$2,000
Total material cost	$40,000	$20,000	$10,000	$6,000
Cost of sales[2]	$30,000	$7,000	$4,000	$2,000
Gross income	$80,000	$8,000	$6,000	$2,000
Working hours	35	12	5	3
Net income per hour	$2,286	$667	$1,200	$667

Based on these findings, the groups developed specific improvement projects. "Weaving dreams" focused on Standardization, proposing to establish standard measurements for each backpack size to save thread and time. "Weaving traditions" focused on Digital Marketing, planning to create social media profiles to upload product videos, explicitly stating the need to "check social media constantly".

[1] Gross income refers to the income obtained from the sale of a unit.

[2] The cost of sales was established, based on the available data, at 20% of gross income.

4.3 Innovation for Women Entrepreneurs (Cochabamba, Bolivia)

This workshop was conducted with 36 women entrepreneurs in Cliza, Bolivia. The participants worked in diverse sectors, including gastronomy (juices, breakfasts), livestock, and bakery [11].

Participants began by creating a "Business Map" of their current operations. For example, a breakfast seller detailed the entire process: from capital (500 Bolivianos, BOB) and ingredients (flour, sugar, oil) to purchase (2 hours), preparation (2 hours, with help from daughters), transport (40 mins), and sales (6 hours). This visual breakdown helped them identify specific bottlenecks, such as the high cost of transport and dependence on family labor.

They then mapped their Challenges, classifying them into four areas:

- Economic: Rising prices of inputs ("everything has gone up").
- Production: Inconsistencies in product quality (e.g., "dough does not ferment well") and environmental factors like frost affecting alfalfa.
- Commercial: Intense competition and lack of transport to reach better markets.
- Management: Lack of recipes/novelties and negotiation skills.

Additionally, participants used generative AI (ChatGPT) and Pinterest to research ideas, leading to significant innovation proposals such as the following:

- Juice Group: One participant planned to research and create specific juice blends for people with diabetes, identifying a niche market. Another proposed method is to preserve seasonal fruit pulp to reduce costs during the off-season.
- Livestock Group: They identified feed costs as a major issue. In a cross-sector solution, they proposed using fruit peels (discarded by the Juice Group) as a low-cost feed supplement.
- Bakery Group: They chose to focus on standardizing recipes to ensure product consistency and "innovating shapes and presentations" to attract more customers.

The final Action Plans were highly concrete. For example, the Weaving group detailed a plan to "search for new designs on Pinterest", "buy wool and needles", and "publish garments on networks", assigning each task to themselves or their daughters.

5 Discussion and conclusions

The results from these three diverse experiences highlight the effectiveness of the Knowledge Integration Actions framework in fostering sustainable, community-led development.

A consistent finding across all interventions was the participants' ability to move from a static view of their reality to a dynamic, strategic perspective. In the entrepreneurship workshops, tools such as the "Business Map" revealed that many participants operated informally and often failed to quantify the value of their own labor. For the Wayúu artisans, the cost analysis was transformative. By visualizing the low return on common products, they spontaneously shifted their strategy towards high-value designs. Similarly, in Bolivia, the "Dream" activity shifted the focus from day-to-day survival to structural transformation. This confirms that local actors effectively apply complex strategic thinking when provided with diagnostic tools that bridge their implicit knowledge and formal business logic.

The results challenge the notion that advanced technology is alien to rural or indigenous contexts. In Bolivia, participants eagerly adopted Generative AI to research nutritional properties, and in Colombia, artisans integrated digital marketing into their core strategy. The key was that these technologies were not presented as solutions in themselves, but as tools to achieve a specific, locally defined goal (e.g., "selling to foreign tourists" or "making juice for diabetics"). This validates the theory of economic hybridity: communities do not want to remain isolated; they want to selectively appropriate modern tools to strengthen their own cultural and economic practices.

Participants supported the interest in the actions and the importance of a contextual approach. In the case of the energy action in Colombia, the participants requested a repeat for more people and communities and proposed improvements to enhance effectiveness. For instance, they asked to develop integration actions near the communities to facilitate

greater participation and to adapt the initial surveys to each community to account for their specific characteristics and be more sensitive in collecting data.

Finally, the results highlight a profound impact on gender dynamics. The vast majority of participants were women (100% in the entrepreneurship workshops). The workshops provided a professional validation of their activities, which are often dismissed as merely domestic chores. In Bolivia, the articulation of "dreams" revealed that business success was inextricably linked to personal well-being and family status. By mastering technical tools, whether for calculating net income or designing a solar maintenance schedule, these women moved from beneficiaries of aid to managers of their own development.

In sum, the pilot actions in Colombia and Bolivia show that the Knowledge Integration methodology offers a robust and valuable alternative to traditional top-down development. By validating local knowledge systems and integrating them with external technical tools, the framework enables vulnerable communities to co-create solutions that are technically sound and culturally pertinent. When positioned as protagonists, communities can diagnose complex problems, design sophisticated infrastructure management models, and innovate within their local economies.

The success of these initiatives lies in selective adaptation, a process in which local actors are not passive recipients of technology but active decision-makers. Rather than having foreign methods imposed upon them, the community negotiates which technologies to adopt. They selectively appropriate external tools, whether it be a solar panel maintenance schedule or a digital marketing platform, and integrate them into their existing social structures to serve their own aspirations. Future work will focus on longitudinal studies to assess the long-term sustainability of these plans and on scaling the methodology to new geographic contexts. Ultimately, this research confirms that the most resilient pathway to sustainable development is one in which knowledge is not transferred but integrated.

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Techno-Economic Assessment of Electrolysis-Based Hydrogen Production in Sri Lanka

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Abstract: Sri Lanka's energy sector is undergoing a rapid transition, driven by the increasing integration of renewable energy sources. Green hydrogen presents a promising pathway to reduce energy curtailment, enhance grid flexibility, and enable both long-term energy storage and power-to-X applications. This study conducts a techno-economic assessment of domestic hydrogen production via alkaline (AEL), proton-exchange membrane (PEM), and solid-oxide (SOEC) electrolysis technologies under current capital expenditure levels and operating conditions. The levelized cost of hydrogen (LCOH) is calculated using a discounted cash flow model that incorporates capital expenditures, operating expenditures, stack-replacement costs, and scenario-specific capacity factors. Five electricity-supply scenarios are evaluated at present electricity costs: (i) grid purchases under a blended time-of-use tariff; (ii) solar-only operation; (iii) wind-only operation; (iv) a hybrid configuration combining daytime solar generation with off-peak grid supply; and (v) curtailed renewable energy available as a fixed daily block. Results indicate LCOH for grid electricity at USD 4.26/kg H_2, followed by the hybrid case at USD 4.80/kg H_2, curtailed-renewables operation at USD 6.85/kg H_2, wind-only operation at USD 7.69/kg H_2, and photovoltaic-only operation at USD 9.05/kg H_2. Sensitivity analysis identifies electricity price, utilization factor, and electrolyzer capital expenditure as the most influential cost drivers. These findings aim to guide decision-makers in integrating hydrogen strategies into Sri Lanka's long-term energy planning and renewable-energy roadmap.

Keywords: Green Hydrogen, Hydrogen Sri Lanka, Levelized Cost of Hydrogen (LCOH), Electrolysis, Techno-economic assessment

1 Introduction

The energy sector is a leading contributor to global greenhouse gas emissions, and its decarbonization is essential for mitigating the impacts of climate change. The rapid integration of renewable energy into the global energy mix marks a transformative shift away from fossil fuels toward clean energy. In 2024, the global share of renewable energy increased by 25% compared with the previous year, with solar photovoltaics the dominant driver of this growth [1]. As a developing nation, Sri Lanka's overall economic stability and industrial growth depend heavily on energy security and affordability [2]. The government established a comprehensive energy policy framework in 2019, set an ambitious target to generate 70% of the country's electricity demand from renewable sources by 2030, and aimed to achieve carbon neutrality in the power sector by 2050 [3].

Sri Lanka experienced rapid growth in solar energy in its energy mix under the national energy policy [4]. Favorable tariff rates and the global reduction in solar PV costs accelerated this growth. However, this rapid integration of variable renewable energy (VRE) led to operational challenges on the national grid. A recent total grid failure has highlighted the vulnerability of system inertia to the inherent intermittency of solar and wind energy [5]. Furthermore, increasing daytime solar penetration has intensified grid flexibility issues, leading to curtailment of renewable generation. The Ceylon Electricity Board (CEB) forecasts substantial energy curtailment from 2026 onwards [6]. Energy curtailment not only reduces the effective utilization of renewable assets but also undermines investor confidence in the energy industry. As the share of VRE continues to rise, the power system requires energy storage technologies, demand-side management, and complementary solutions to absorb surplus generation and enhance flexibility [7]. However, current developments in energy storage projects in Sri Lanka remain in their early stages and are progressing more slowly than the country's current and future demand. The major 600-MW Maha Oya pumped-storage project is still in the detailed design stage and is expected to be commissioned by 2032 [6]. Also, integration of utility-scale battery energy storage systems (BESS) is still in its early stages. While initial projects are underway and progressing slowly, large-scale deployment has yet to materialize. In this context, Sri Lanka needs to explore emerging energy storage technologies, such as hydrogen storage, to enhance power system resilience and flexibility [8].

Hydrogen emerges as a versatile energy source and is increasingly regarded as a pivotal energy carrier in the path to net-zero targets. It offers opportunities to reduce the carbon footprint in power generation, industry, and hard-to-abate sectors such as maritime shipping and aviation [9]. Beyond these sectoral applications, hydrogen is widely recognized as a reliable energy storage medium for storing surplus renewable energy over medium- to long-term durations [10]

[11]. Furthermore, hydrogen plays a crucial role in hydrogen-driven Power-to-X (PtX) applications. PtX enables the conversion of renewable electricity into a wide range of energy carriers and value-added products. By producing green hydrogen, surplus energy can be stored and later used to produce synthetic methane, synthetic fuels, and e-fuels such as methanol, ammonia, and kerosene, as well as feedstocks for fertilizers, petrochemicals, and the steel industry [12].

However, integrating the hydrogen supply chain depends heavily on hydrogen's technical viability and production cost [13]. As Sri Lanka begins hydrogen development, techno-economic evaluations are vital for assessing feasibility, costs, and policy implications. This study assesses the levelized cost of electrolysis-based hydrogen production in Sri Lanka across multiple scenarios, focusing on renewable energy, energy curtailment, and tariff-based pricing, and offers novel insights to guide the hydrogen economy.

1.1 Background

Hydrogen Economy in Sri Lanka: Current Literature and Policy Frameworks

Despite growing global research on hydrogen energy, studies focused on Sri Lanka remain limited and are still emerging. [14] A techno-economic feasibility study assessed the integration of solar PV with on-site hydrogen production and storage for off-grid telecom base stations in Sri Lanka. In 2023, the country established a national hydrogen roadmap that positions green hydrogen as a driving force for renewable integration, energy security, and future exports. It highlights the potential of 40 GW of offshore wind and curtailed renewables to support the development of a hydrogen economy in the country [15]. Furthermore, [16] critically evaluates the national hydrogen roadmap by comparing it to the hydrogen strategies of other leading global economies. The BICOST IX Energy Storage Conference Report (2023) identified green hydrogen as a viable solution for long-duration energy storage and grid balancing in Sri Lanka [8]. Also, [17] highlights the policy and strategic importance of green hydrogen for Sri Lanka's sustainable development. Similarly, Sri Lanka's long-term generation expansion plan 2025–2044 supports the integration of hydrogen as both an energy carrier and a grid-balancing solution, mandating that future gas turbines and internal combustion engines be hydrogen-compatible [6]. Most recently, Sri Lanka's National Policy on Renewable Hydrogen (Final draft, May 2025) recognizes hydrogen as the third energy carrier to complement the country's energy transition goal. The policy emphasizes hydrogen's role in decarbonizing hard-to-abate sectors such as fertilizer production, steel, cement, and heavy transport, while also positioning the country as a potential exporter of renewable hydrogen [18].

Nevertheless, the existing literature has neither conducted a techno-economic assessment of hydrogen production nor evaluated LCOH, leaving a critical research gap in quantifying the economic feasibility of hydrogen deployment in Sri Lanka. Therefore, this study is significant for Sri Lanka as it provides context-specific techno-economic insights into hydrogen production costs, thereby supporting ongoing policy development, deployment strategies, and research initiatives in the hydrogen domain.

2. Data and Methods

2.1 Data Sources

This study employs data sourced from international corporate reports, peer-reviewed research publications, government and intergovernmental reports, and publicly available electricity pricing data. The literature review also provides data on electrolysis system efficiencies, degradation rates, and methodological approaches relevant to LCOH assessments. Electricity data were sourced from present tariff structures, time-of-use pricing schedules, and generation statistics published by the Public Utilities Commission of Sri Lanka (PUCSL) and the CEB.

2.2 Electrolysis hydrogen production

Electrolyzer technologies

Hydrogen production via water electrolysis involves splitting water into hydrogen and oxygen using electrical energy. Electrolytic hydrogen production still accounts for only a very small share of global production (less than 100 kt H_2 in 2023) compared to other hydrogen production pathways [19]. Figure 1 illustrates the widely adopted hydrogen production methods in the industry, presented in a color-coded format. Throughout the electrolysis process, multiple technologies have been developed based on the system's electrochemical characteristics, including the ion transport medium, electrode types, catalysts, cell voltage, current density, and operating pressure and temperature [20]. Alkaline Electrolyzers (AEL) are the most commercially mature and widely deployed technology, with a technical readiness level (TRL) of 9 [21]. They are considered highly cost-effective due to the use of non-noble electrocatalysts and offer

a durable stack lifetime of up to 100,000 h [22]. Proton Exchange Membrane (PEM) electrolyzers are also commercially utilized. They are increasingly adopted due to their higher current density and faster dynamic response than AEL, making them well-suited for coupling with VRE [23]. However, PEM systems require precious-metal catalysts, typically platinum and iridium, resulting in higher capital costs than AEL. Furthermore, Solid oxide electrolyzers (SOECs) offer significant potential for higher energy efficiency, operating at elevated temperatures of 600-850 0C. Although they are not commercially widespread (TRL 8), they use both electricity and heat and can achieve higher efficiency than low-temperature electrolyzers [24]. However, key challenges of SOECs include material degradation under high-temperature operation, limited stack lifetimes, and relatively high capital costs [22].

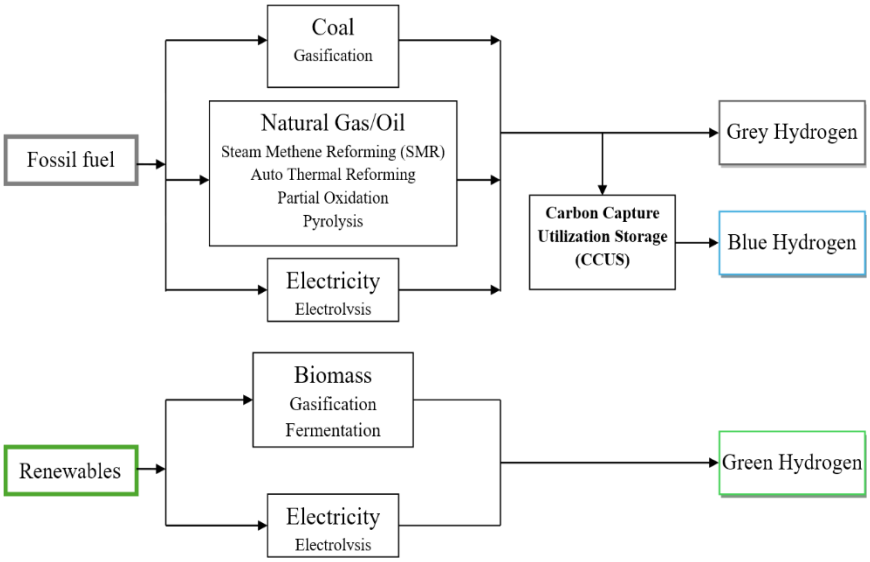


Fig. 1 Common hydrogen production pathways and their color-based classification

Specific Energy Consumption and Efficiency

Specific energy consumption (SEC) is a key parameter for an electrolyzer, quantifying the electrical energy required to produce 1 kg or 1 Nm3 of hydrogen. The electrolyzer stack SEC can be derived from Equation 1.

$$SEC_{stack} = \frac{P_{elec}}{\dot{m}_{H_2}} \quad (1)$$

Where $\dot{m}_{H_2}$ is the hydrogen production rate in kg/h or Nm^3/h, P_{elec} In kW is the electrical power input to the electrolyzer. The efficiency (ɳ stack) of the electrolyzer is inversely related to the SEC of the stack. It is often referred to as the lower heating value (LHV) of hydrogen, which is 120 MJ/kg (33.3 kWh/kg H2).

$$\eta_{stack} = \frac{LHV_{H_2}}{SEC_{stack}} \quad (2)$$

It is common in the literature to report the system-level specific energy consumption (SEC_{system}) and system efficiency (η_{system}), which account for all other balance-of-plant (BoP) components such as water purification, cooling, gas drying, and power supply. These additional subsystems contribute to both capital cost and energy consumption, resulting in overall system efficiency being lower than the stack efficiency.

CAPEX Cost and OPEX Cost of an Electrolyzer System

The electrolyzer system CAPEX cost considered here includes the electrolyzer stack, balance of plant (water treatment, gas purification, pumps, and other process equipment), engineering, procurement, and construction (EPC) costs, and contingencies. To align with current market conditions, only data published from 2020 onward was considered, and all prices were adjusted to constant 2024 USD values for comparison. Figure 1 presents CAPEX data for AEL, PEM, and SOEC systems, compiled from credible international sources including the IEA [19], U.S. DOE Strategic Analysis [25]

and Hydrogen Program Records [26], Hydrogen Europe [24], Hydrogen Observatory [27], ISPT [28], NREL, ICCT [29], as well as regional studies from Japan [23] and Australia [30].

AEL systems show the lowest median costs (1,413 USD/kW), with regional variation ranging from 778 USD/kW in Australia [30] to around 2,500 USD/kW in recent EU reports [27]. PEM systems exhibit higher median values (2,394 USD/kW), with EU data reaching up to 2,700 USD/kW [27]. SOECs are reported in only two sources but remain significantly more expensive, with estimates around 2,300 USD/kW in EU/US reports [29] and higher values (5,843 USD/kW) in Hydrogen Europe [24]. For subsequent LCOH calculations, the median values for each technology were used as the base values.

Operational expenditure (OPEX) is divided into fixed and variable components. Fixed OPEX, covering water, chemical, testing, maintenance, labor, and insurance costs, is assumed to be 2–5% of system CAPEX in the literature [26] [27]. Variable OPEX is dominated by electricity costs, as discussed in section 2.5.

Stack lifetime and stack replacement

Electrolyzer stacks have a finite operating lifetime due to multiple degradation mechanisms, including catalyst dissolution, membrane thinning, electrode delamination, gas crossover, and thermal stresses [31]. Stack replacement is a significant CAPEX component, with industry benchmarks typically estimating it at 10–30% of total electrolyzer CAPEX in LCOH calculations [32] [27] [26].

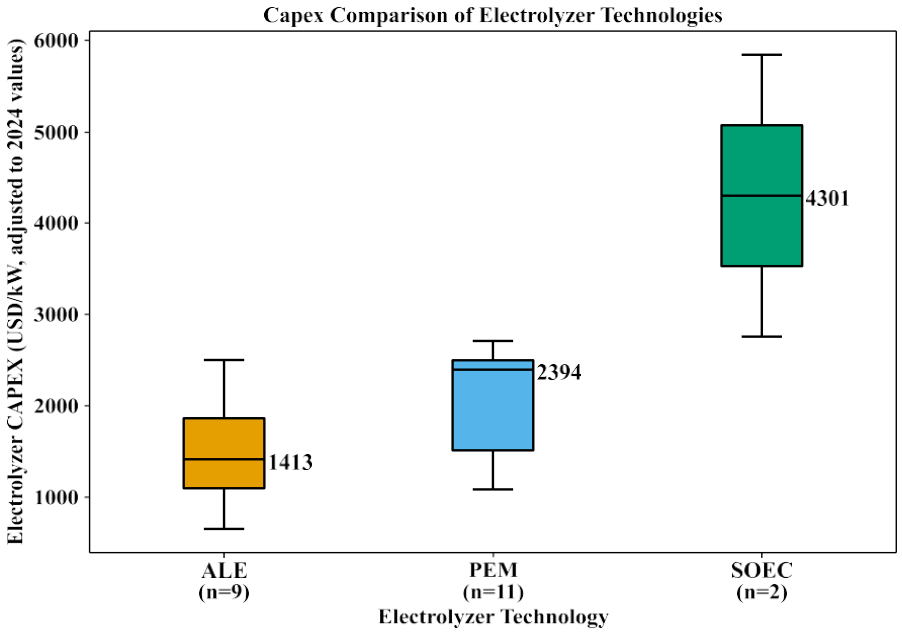


Fig. 2 CAPEX cost variation across electrolyzer technologies

Comparison of electrolyzer technologies

Table 1 compares the technical characteristics of three electrolyzer technologies, as reported in [20], [22], [33], [34], and [35].

Table 1: Comparison of main water electrolyzer technologies

Parameters	AEL	PEM	SOEC
Development Stage	Commercial	Commercial	Early commercial
Electrolyte	Liquid KOH/NaOH (20%-40%)	Solid polymer (Nafion)	

Solid ceramic

Charge carrier OH^- H^+ O^{-2}

Electrodes and catalysts Anode: Ni, Fe Cathode: Ni/Ni alloys

Anode: Pt, IrO_2, RuO_2 Cathode: Pt, Pt/C

Anode: LSM–YSZ composite Cathode: Ni-cermet

Reactions	Anode reaction $2\ OH^- \rightarrow ½\ O_2 + H_2O + 2\ e^-$ Cathode reaction $H_2O + 2\ e^- \rightarrow H_2 + 2\ OH^-$	Anode reaction $H_2O \rightarrow ½\ O_2 + 2\ H^+ + 2\ e^-$ Cathode reaction $2\ H^+ + 2\ e^- \rightarrow H_2$	Anode reaction $O^{2-} \rightarrow ½\ O_2 + 2\ e^-$ Cathode reaction $H_2O + 2\ e^- \rightarrow H_2 + O^{2-}$
Operating Temperature (^0C)	70 - 90	50-80	800-1000
Operating Pressure (bar)	<35	<80	1-10
Current density (mA/cm^2)	0.2-0.6	0.2-2	0.3-1
Cell voltage (V)	1.8-2.4	1.8-2.4	0.95-1.3
$SEC_{system}(kWh/kgH_2)$	50-78	50-83	38 -48
Stack lifetime (full load hours)	60,000-100,000	50,000-90,000	20,000-50,000

2.3 LCOH Framework

The LCOH is the key parameter in a techno-economic assessment, representing the average cost of producing one unit of hydrogen over the entire project lifetime. The LCOH combines project CAPEX and OPEX, system-specific technical parameters, and a hydrogen production discount rate to provide a basis for financial decision-making. The study follows the LCOH economic model, which represents the ratio of the Net Present Value (NPV) of total costs to total hydrogen production over the project lifetime.

$$\text{LCOH} = \frac{\text{Net present values of total cost}}{\text{Net present value of hydrogen Production}} \quad (3)$$

Equation 4 is used to calculate LCOH, where C0 represents the CAPEX in year 0 and Cs is the stack replacement cost in year t. Ot and Et represent the OPEX and electricity costs in year t. MH2t is the hydrogen production in year t, and r represents the discount rate, and n is the economic lifetime of the project in years.

$$\text{LCOH} = \frac{C_0 + \sum_{t=1}^{n} \frac{C_t + O_t + E_t}{(1+r)^n}}{\sum_{t=1}^{n} \frac{M_{H2_t}}{(1+r)^n}} \quad (4)$$

Based on the literature reviewed, the key parameters used for the LCOH calculation are summarized in Table 2.

Table 2: LCOH parameter assumptions for the study

Parameter	Units		Value	
System Capacity	MW		10	
		AEL	**PEM**	**SOEC**
SEC of the electrolyzer system	kWh/kgH2	55	50	40
Stack lifetime	hours	80,000	60,000	40,000
Capex cost	USD/kW	1,500	2,100	4,300
Stack replacement cost	% of Capex		30	
O&M Cost	% of Capex		3	
Discount rate	%		8	
Project lifetime	Years		25	

2.5 Modeling of electricity cost scenarios

The cost and source of electricity are critical factors in the LCOH, as they govern both operating expenditures and electrolyzer utilization. In this study, five hypothetical scenarios are defined to capture the diversity of current and future expansion of the country's electricity sector.

Scenario 1: Grid Electricity under Time-of-Use (TOU) Tariff

The electrolyzer is supplied entirely from the national grid, with electricity purchased under a blended tariff reflecting peak, off-peak, and daytime rates. This scenario uses existing infrastructure and ensures high utilization. The grid emission factor was set to 0.648 kg CO2/kWh to evaluate the associated CO2 emissions [4].

Scenario 2: Solar Photovoltaic (PV) – Dedicated Supply

In this scenario, the electrolyzer is directly coupled to a solar PV installation and operates during daytime hours (6 hours/day). This reflects the rapid expansion of PV capacity in Sri Lanka and leverages the declining costs of PV. The main limitation is the relatively low-capacity factor (20-25%), which limits electrolyzer utilization.

Scenario 3: Wind – Dedicated Supply

Wind energy is used as the sole power source for the electrolyzer. Compared with solar, wind resources in the country generally exhibit higher capacity factors of 25–35%, enabling longer daily operating hours. Wind output variability still poses integration challenges, but wind-driven electrolysis benefits from higher annual utilization than PV-only systems.

Scenario 4: Hybrid Case: PV with Off-Peak Grid Supply

A hybrid configuration is modeled that combines daytime PV generation with off-peak grid electricity, thereby extending operational hours and improving electrolyzer utilization. This reduces intermittency constraints while avoiding higher peak tariffs. The hybrid approach balances cost and utilization, yielding more favorable economics than PV-only or grid-only operation.

Scenario 5: Curtailment-Driven Operation

In this scenario, the electrolyzer utilizes renewable electricity that would be curtailed due to oversupply. Curtailment is already emerging during midday solar peaks, and its frequency is expected to increase as variable renewable penetration grows. Hydrogen production from curtailed energy provides a low-marginal-cost input but is limited by unpredictable availability. This pathway is attractive because it converts surplus renewable electricity into storable hydrogen, with electricity costs effectively zero.

Table 3 summarizes the electricity supply scenarios, including applicable electrolyzer utilization factors and electricity costs.

Table 3: Electricity supply scenarios with prices (4 h/day)

No	Scenario	Electricity Cost (LKR/kWh)	Electricity cost USD/kWh	Utilization Factor	Pricing data
1	Grid only (Time of Use (TOU) blended)	15.55	0.0518	0.95	Weighted CEB industrial rate 3 TOU 12 h day @ 14.00 LKR + 4 h peak @ 27.00 LKR + off-peak @ 11.00 LKR = 15.17 + 2.5% tax

2	Solar-PV only (5 h/day)	17.62	0.0587	0.20	Ground-mounted solar PV tariff (≤10 MW)
3	Wind only (8.5 h/day)	23.83	0.0794	0.35	Onshore wind Flat tariff rate (≤10 MW)
4	Hybrid: PV + Off-peak grid (13 h/day)	13.72	0.0457	0.54	Weighted (5 h PV at 17.62 LKR + 8h grid at 11.00 LKR + 2.5% tax)
5	Curtailed RE	0.00	0.00	0.17	Zero electricity cost

Note: Currency conversion is applied at a rate of 1 USD = 300 LKR. Grid tariff values are based on the CEB industrial rate and Time-of-Use (TOU) pricing, inclusive of a 2.5% tax [36]. Solar-PV and wind tariff rates correspond to ≤10 MW feed-in tariffs published by CEB (effective June 2025) [37].

Key Assumptions

For all scenarios, a 10 MW electrolyzer system is assumed, with sufficient power availability to operate it at full load. Solar PV and wind systems are oversized to ensure continuous full-load operation within their respective availability windows, while part-load operation and load-following are not considered. In the curtailed renewable energy scenario, electricity is assumed to be available at zero marginal cost. Furthermore, across all scenarios, additional subsidies, tax incentives, or revenue income are not considered.

3 Results and Discussion

Across all technologies, AEL consistently demonstrates the lowest LCOH in all scenarios, ranging from 4.26 to 9.05 USD/kg H_2. For PEM, it ranges from 4.55 to 10.35 USD/kg H_2, while SOEC systems remain the most expensive, at 5.6–15.0 USD/kg H_2, due to higher capital costs and faster stack degradation rates. Figure 2 shows the variation in LCOH for electrolyzer technologies across the five scenarios.

Figure 3 illustrates the variation in LCOH across the three electrolyzer technologies under the modeled scenarios. In the renewable electricity cases, the calculated LCOH ranges from 6.85 to 15 USD/kg H_2. According to the IEA, the current cost of hydrogen production from renewable electricity is estimated at USD 4-18/kg H_2, with significant variation across regions and technologies. Under its Net Zero Emissions by 2050 (NZE) Scenario, the IEA projects that these costs will decline by about half, reaching USD 2-9/kg H_2 by 2030 [19].

Given the lower LCOH across all scenarios, AEL is selected for further analysis of hydrogen production potential and sensitivity. This focus reflects its techno-economic advantage, with a higher maturity level and lower CAPEX, making it the most suitable baseline technology for deployment under local energy system conditions. Figure 3 shows the cost breakdown and hydrogen production of AEL under each scenario.

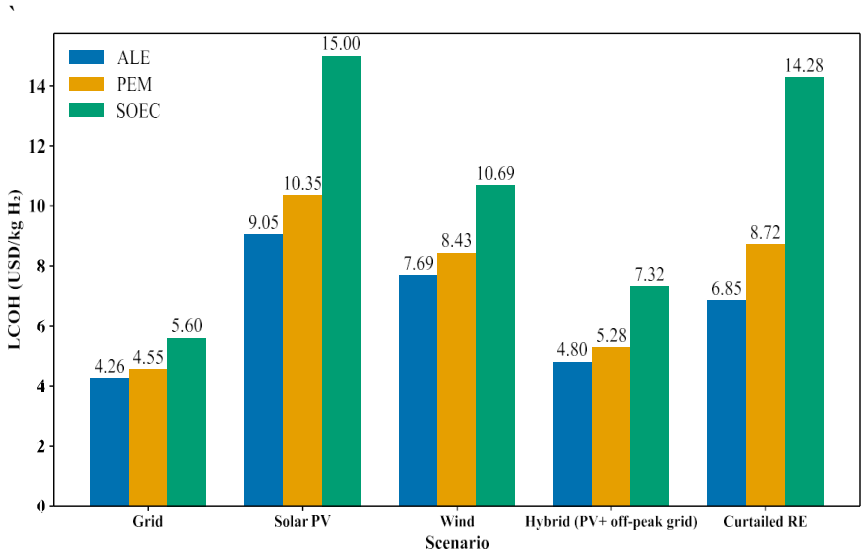


Fig. 3 LCOH variation of three electrolyzers

The Grid-only case achieves the lowest LCOH of 4.26 USD/kg H_2 and the highest annual hydrogen production, but results in significant emissions (totaling 539,387 tons of CO2). In this scenario, stack replacements are scheduled at the 10th and 20th years, respectively. The hybrid scenario offers a balanced outcome, combining moderate costs and hydrogen production with reduced emissions, resulting in a total of 183,959 tons of CO_2. In this case, stack replacement is scheduled for the 17th year of operation.

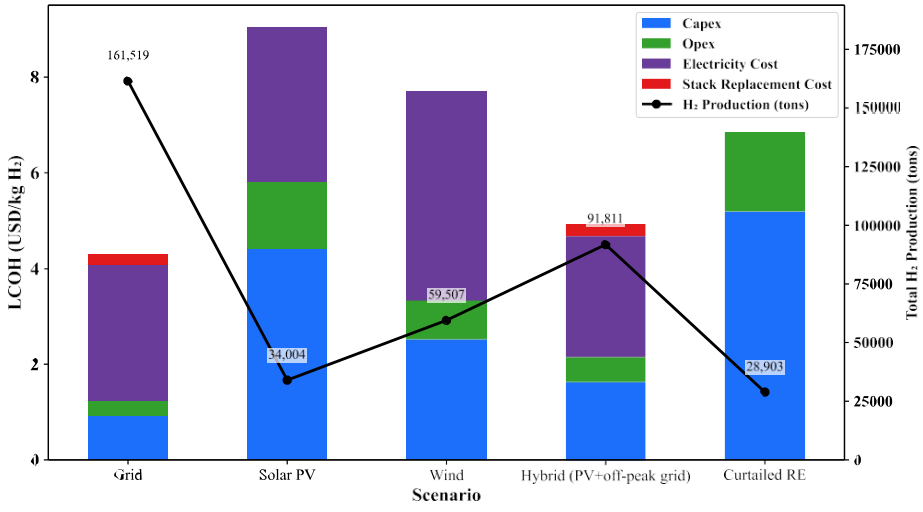


Fig. 4 Cost breakdown of ALE across scenarios, with hydrogen production shown on the secondary axis

3.1 Sensitivity Analysis

Sensitivity analysis was carried out by varying parameters within realistic ranges: CAPEX ±30%, OPEX ±20%, electricity price ±25%, utilization factor ±10%, stack replacement cost ±30%, and the discount rate from 4% to 12%. This approach captures practical uncertainties and highlights the most influential drivers of LCOH.

As shown in Figure 5, the electricity price is the dominant driver of LCOH across all scenarios except curtailed renewable energy. For renewable hydrogen pathways, CAPEX, utilization factor, and discount rate significantly influence costs, with higher discount rates increasing hydrogen production costs. In contrast, OPEX variations have only a marginal effect. Stack replacement costs are relevant only in the grid-only scenario, as reduced operating hours in other cases limit the need for replacements. Overall, the results show that hydrogen cost competitiveness is primarily determined by access to low-cost electricity, maximizing electrolyzer utilization, minimizing system CAPEX, and maintaining favorable financing conditions through lower discount rates.

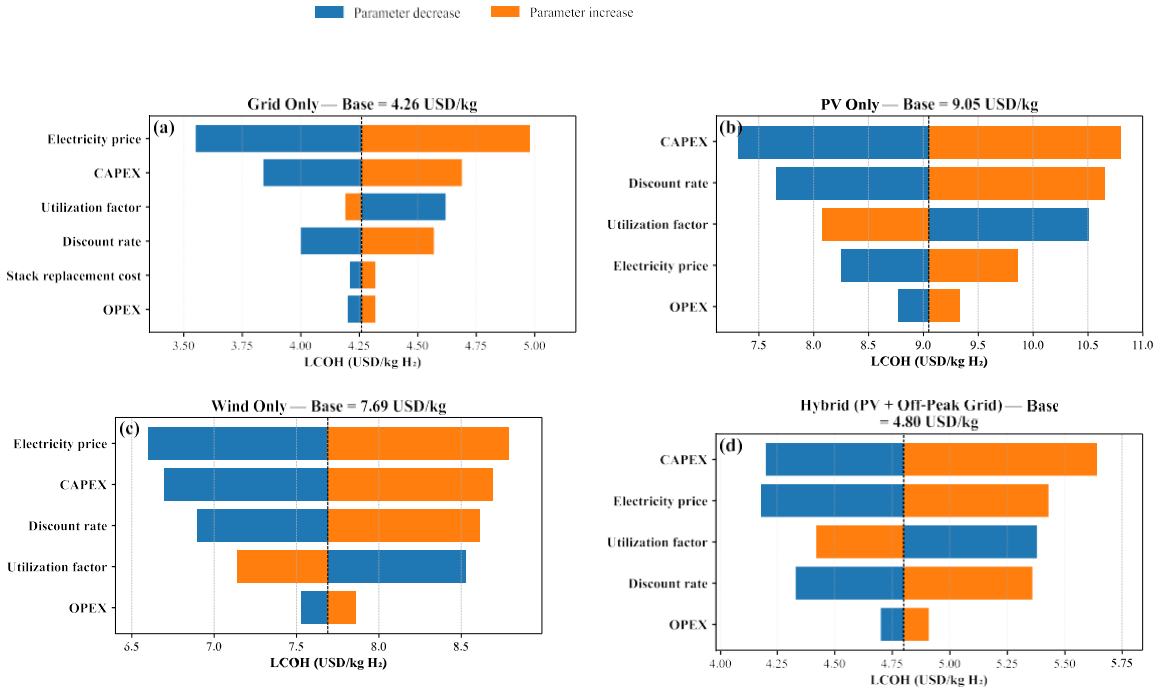


Fig. 5 One-way sensitivity analysis of the LCOH of ALE across five electricity-supply scenarios: (a) Grid only, (b) PV only, (c) Wind only, (d) Hybrid (PV + off-peak grid), and (e) Curtailed RE

4. Conclusions

This study evaluated context-specific LCOH under multiple scenarios to produce both grey and green hydrogen at current electricity pricing structures and future curtailment projections. Among the technologies assessed, AEL consistently delivers the lowest hydrogen costs, making it the most viable near-term option for full-load operation. The grid-only case achieves the lowest cost but at the expense of high CO_2 emissions, while renewable-only pathways are clean but more expensive and constrained by utilization limits. Hybrid scenarios offer balanced solutions that combine cost advantages with lower emissions. Overall, electricity cost, utilization rates, system CAPEX, and project financing conditions are the strongest drivers of hydrogen competitiveness in Sri Lanka. These findings provide a valuable foundation for further evaluations aimed at integrating hydrogen into the national energy system. Addressing these key cost drivers through policy support, investment incentives, and stakeholder partnerships will be essential to advance Sri Lanka's vision of hydrogen as a strategic energy carrier, as outlined in the draft National Policy on Renewable Hydrogen.

Future works

Future studies should conduct detailed techno-economic modeling that addresses the dynamic behavior of hydrogen electrolyzer under variable renewable generation. This includes incorporating local weather and resource data to capture part-load efficiency and dynamic response. The analysis should be extended to include dynamic tariffs, by-product revenues, stack degradation and replacement under cycling, water and land constraints, hydrogen storage, and policy-driven scenarios such as CAPEX declines and government subsidies. These models would provide concrete data to support Sri Lanka's efforts in deploying renewable hydrogen technologies.

Funding Note: This study received no external funding.

Data Availability Statement: The data presented in this study are available upon request from the corresponding author.

Conflicts of Interest: The author declares no conflict of interest.

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Integrating Circular Economy Principles into the Banking Sector: A Framework for Sustainable Financial Operations

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Abstract: The banking sector in Sri Lanka, though non-industrial, exerts a considerable environmental impact through its extensive branch networks, significant energy and water consumption, operational waste generation, and material-intensive infrastructure. This study develops a practical, scalable Circular Economy (CE) framework tailored for banking operations, transforming financial institutions into resource-efficient, low-impact entities. A mixed-methods approach was employed, encompassing quantitative analysis of resource consumption across 15 bank branches and qualitative stakeholder interviews. The assessment covered key operational domains, including energy, water, waste management, digital transformation, procurement, and indoor environmental quality.

Findings indicate the presence of energy-efficient lighting and HVAC systems, yet limited integration of renewable energy, water reuse, and systematic waste segregation. Benchmarks were established for energy use, organic waste, paper waste, and polythene waste. The study also reveals minimal uptake of digital document management, the absence of green procurement policies, and limited adoption of modular assets and lifecycle-based maintenance strategies.

The proposed CE framework introduces targeted interventions in solar PV deployment, low-flow water fixtures, paperless banking processes, the reuse of decommissioned assets, and supplier sustainability compliance. It aligns with national sustainability directives (Gazette 2339/09) and positions the Sri Lankan banking sector as a potential leader in sustainable service-based infrastructure. A review mechanism, including an Energy Star rating system, KPI reviews, staff progress surveys, performance recognition, and independent audit verification, ensures continuous evaluation and improvement of recommendations. By embedding CE principles, the framework contributes to advancing Sri Lanka's transition toward a low-impact, resource-efficient financial sector.

Keywords: Circular Economic Concepts, Banking Sector, Green Procurement, Sustainable Financial Operations, Digital Transformation

1 Introduction

1.1 Background

Buildings play a crucial role in any economy, but have a significant environmental impact. Building premises are among the largest consumers of energy, water, and material resources, and they generate substantial waste. As environmental performance becomes an increasing concern, there is an urgent need for strategies and actions to make building operations more sustainable.

The banking sector, a key component in national development, operates a wide network of branches, Automated Teller Machines (ATMs), Cash Recycler Machines (CRMs), digital infrastructure, and logistics, all of which consume significant energy and resources. Frequent upgrades, renovations, and technology replacements contribute to increased waste generation and environmental pressure. While Sri Lanka's regulatory frameworks, as set out in the *Gazette Extraordinary No. 2339/09 (2023)*, mandate energy benchmarking for institutions under Group 641 (Monetary Intermediation), there is a notable absence of circular economy (CE) integration in day-to-day banking operations. However, there is limited guidance on how financial institutions can effectively implement circular energy practices to optimize resource usage and reduce waste. The framework will focus on renewable energy adoption, energy efficiency, waste reduction, and lifecycle management of energy assets, in line with circular economy principles.

The study will examine international best practices and assess their relevance to the Sri Lankan context. Through stakeholder discussions, operational audits, and literature reviews, the research will develop a practical model for circular energy and resource management in the banking sector, enhancing resilience, compliance, and sustainability performance.

This research seeks to bridge this gap by developing a Circular Economy Framework specifically tailored for the banking sector in Sri Lanka. It will explore resource efficiency, digital transformation, lifecycle asset management,

and waste-minimization strategies applicable across banking operations. The aim is to move beyond building-level energy use and align with both international best practices and national compliance requirements.

1.2 Problem Statement

The financial sector, particularly its physical infrastructure, remains underexplored despite its high resource consumption and long working hours, with constant energy, water, and cooling needs. In Sri Lanka, the banking sector comprises over 26 licensed commercial institutions operating more than 5,815 branches islandwide. This creates a large environmental footprint, whereas most Circular Economy applications focus on manufacturing, construction, or municipal waste management.

As a result, the banking sector faces several systemic sustainability challenges, and current sustainability practices are largely fragmented and lack a structured, circular approach. Most institutions focus narrowly on energy-saving technologies, such as efficient lighting or HVAC systems, without addressing broader circular-economy principles of resource circularity, reuse, lifecycle extension, and waste conversion into useful resources.

1.3 Research Objectives

The aim of this research is

- To develop a comprehensive framework that applies circular economy concepts to the banking sector premises in Sri Lanka, enhancing environmental sustainability and operational efficiency.
- The objectives of the study are as follows:
- To analyze global best practices in circular economy adoption across the financial and commercial building sectors and assess current practices and gaps in Sri Lankan banks.
- To develop a Circular Economy Framework that integrates renewable energy and energy efficiency, Water conservation, Waste reduction and recycling, Digital transformation, lifecycle asset management, and indoor environmental quality (IEQ).
- To propose a scalable and practical Circular Economy framework for implementation across banking operations in Sri Lanka.

1.4 Significance

This research provides the first structured CE framework for Sri Lanka's banking sector. It addresses compliance with energy regulations, enables cost savings, enhances operational efficiency, and supports national sustainability goals, including the UN Sustainable Development Goals (SDGs).

2 Literature Review

2.1 The Circular Economy Concept

Circular Economy (CE) departs from the linear "take-make-dispose" model by promoting resource circularity. CE principles emphasize reducing the use of virgin materials, reusing resources, extending product lifecycles, and regenerating ecosystems (Ellen MacArthur Foundation, 2013). Definitions vary: Ghisellini et al. (2016) emphasize restorative systems; Kirchherr et al. (2021) frame CE as a business model centered on reduction, reuse, and recycling; Haas et al. (2015) highlight the closing of ecological and economic loops.

Beyond environmental gains, CE creates economic opportunities by transforming waste into valuable inputs. It also encourages systemic change in corporate responsibility, extending beyond shareholder interests to societal and ecological stakeholders.

2.2 CE in the Financial Sector

Though service-oriented, banks directly impact sustainability through their building operations and indirectly through their financial portfolios. UNEP FI (2020) notes that banks influence sustainability outcomes by financing or divesting from particular industries. However, internal operations themselves demand attention: large branch networks consume substantial amounts of energy and water while generating waste. Applying CE to banking premises can reduce resource footprints while signaling commitment to sustainability.

International examples include:

- **ABN AMRO (Netherlands)** – reused demolition materials in headquarters refurbishment.
- **DBS Bank (Singapore)** – introduced paperless transactions and solar energy integration.
- **Barclays (UK)** – implemented green-certified branches with advanced energy management.

These models illustrate the feasibility of embedding CE into financial infrastructure.

2.3 Sustainable Building Principles

Banks primarily operate from office-like premises. Sustainable building practices -energy optimization, material reuse, water efficiency, and indoor environmental quality -are crucial. Energy represents 85–95% of lifetime building emissions [11]. Water efficiency, often overlooked, can be achieved through low-flow fixtures, rainwater harvesting, and greywater reuse [17].

Indoor environmental quality (air quality, acoustic comfort, and lighting) also significantly affects staff health and productivity. Integrating CE into building design and retrofits, therefore, directly benefits banking operations.

Buildings account for approximately 40% of global material use and are primary sources of solid waste [15]. Sustainable building practices integrate environmental stewardship, social responsibility, and economic viability. Hill and Bowen [7] propose four key pillars: social (quality of life, health, and safety), economic (financial viability and job creation), biophysical (responsible resource use and waste minimization), and technical (durability, functionality, and quality).

Energy optimization strategies include efficient window coverings, daylighting, lighting controls, and LED adoption. Water optimization encompasses low-flow fixtures, greywater systems, rainwater harvesting, and pressure reduction. Material optimization emphasizes durability, local sourcing, recyclability, and non-toxic specifications.

2.4 Research Gaps

Despite growing literature on the circular economy in manufacturing and construction, detailed frameworks for implementing CE in service-based financial sectors, especially in developing countries, remain limited. Key gaps include:

- Lack of sector-specific CE frameworks for financial institutions
- Insufficient research on resource optimization in banking facilities
- Limited empirical studies on digitalization-circularity intersections
- Few case studies on CE application in existing banking infrastructure
- Need for standardized performance indicators for circular banking operations

This study responds to these gaps by developing a CE framework tailored to the banking sector.

3. Methodology

To investigate and develop a comprehensive Circular Economy (CE) Framework for sustainable banking premises in Sri Lanka, this study employs qualitative and quantitative methods. It adopts an exploratory, evidence-based approach to examine the practical implementation of CE principles. The research framework is constructed through operational indicators derived from an extensive literature review, aligned with international best practices, and benchmarked against local case studies.

- The design is structured to
- Identify existing practices and performance gaps.
- Benchmark environmental performance indicators against the local/ international standards.
- Develop a replicable and scalable framework for Circular Economy -based sustainable bank building operations.

3.1 Population, Sample Selection, Data Collection, and Analysis

The study is confined to Colombo District, Sri Lanka's commercial and administrative hub, where a significant number of bank branches are concentrated. This region offers a diverse mix of 15 government- and private-sector banks operating across a range of building types, making it an ideal setting for assessing infrastructure, energy use, and sustainability initiatives. The target population includes Government and private banking institutions.

Purposive and random sampling techniques are employed to ensure a representative mix of institutions. These branch premises reflect a mid-range operational capacity, which is ideal for drawing generalizable insights into the potential for Circular Economy adoption within the broader banking sector.

Data collection was conducted using structured questionnaires and interviews. The primary tool was a structured survey instrument, developed based on ten operationalization indicators identified from the literature and global CE practices:

1. Building Envelope & General Information
2. HVAC Systems
3. Lighting and Electrical Systems
4. Renewable Energy Utilization
5. Water Usage & Wastewater Systems
6. Waste Management Practices
7. Asset Lifecycle & Procurement
8. Indoor Environmental Quality (IEQ)
9. Digitalization & Paper Reduction
10. Circular Business Practices & Stakeholder Engagement

The collected data has been analyzed using descriptive statistical tools (Excel/SPSS) to benchmark institutional performance against Circular Economy (CE) metrics, with reference to international standards, Gazette No. 2339/09, and best global banking practices.

3.2 Quantitative analysis covers:

- Energy and water consumption (kWh/month, L/day/head)
- Waste generation and recycling (% reused)
- Digitalization indicators (e-transactions, paper reduction)

3.3 Qualitative analysis examines:

- Challenges and opportunities in CE adoption
- Organizational attitudes toward green finance and stakeholder engagement
- Staff perceptions of indoor environmental quality and operational efficiency.

4. Results and Analysis

Quantitative data were benchmarked against local (Gazette 2339/09) and international standards. Regression analyses assessed correlations between building size and energy use, or employee numbers and water consumption. Qualitative data were thematically analyzed to identify barriers and opportunities.

To assess resource performance, energy performance, and sustainability behaviors across the banking sector, key components of monthly energy consumption, water use, waste generation, and paper reduction targets were analyzed using field data collected from selected branches.

4.1 Energy Mix

Table 1. Energy Mix Analysis

Category	Energy Consumption (kWh)	Percentage (%)
HVAC (Air Conditioning)	70,483.05	55.00%
Lighting	25,630.20	20.00%
Plug Loads (Computers, Equipment)	25,630.20	20.00%
Others (Pumps, Elevators)	6,407.55	5.00%
Total Energy Use	**128,151.00**	**100.00%**

Specific Energy Density analysis shows a strong R^2 of 0.8502, supporting the notion that branch size is a major driver of energy demand in the banking sector. The total floor area of the bank branch explains 85.02% of the variation in monthly energy consumption. This indicates a strong positive correlation; as building size increases, energy consumption tends to increase as well.

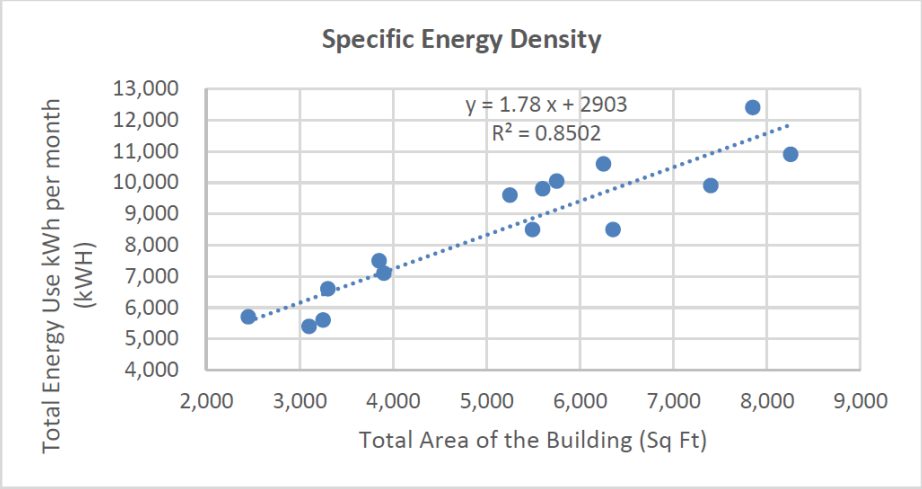


Fig. 1 Specific Energy Density

Waste Management and Digitalization: Regression analysis of the sampled branches established benchmark values for weekly waste generation as follows,

- Organic Waste: 0.84 kg/employee/week
- Paper Waste: 0.39 kg/employee/week
- Polythene Waste**:** 0.28 kg/employee/week

The analysis revealed that in biodegradable (organic) waste generation, there is a clearer linear relationship between staff count and biodegradable (organic) waste generation in banking premises.

The positive slope (0.8409) indicates that each additional employee contributes approximately 0.84 kg of organic waste per week, establishing this as the benchmark rate. Biodegradable waste mainly arises from staff-related activities of lunch leftovers, canteen use, and pantry operations, confirming that waste management strategies should align with branch staff size, including the following,

- Provide organic waste bins proportional to staff numbers.
- Conduct awareness programs to reduce food waste.
- Introduce composting at larger branches.
- Continuously monitor waste trends to refine the model.

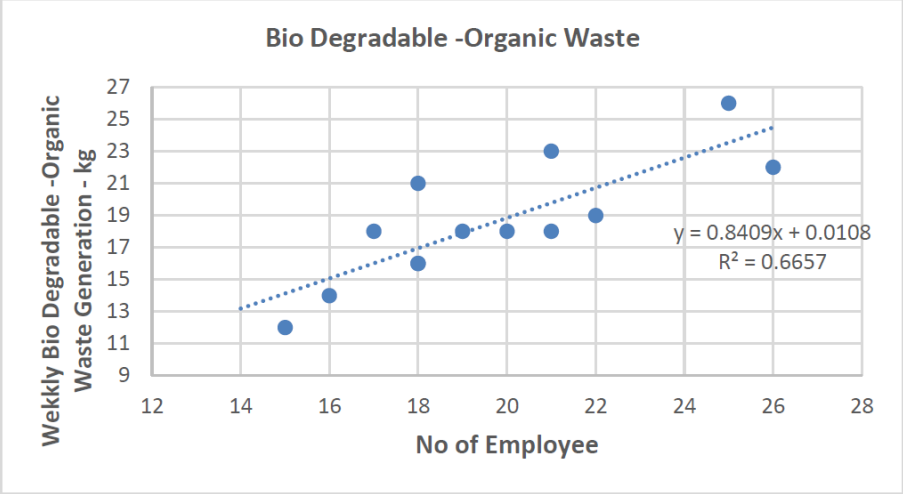


Fig 2 Organic Waste Generation over the Number of Employees

However, since employee count alone does not fully explain waste generation, other factors, including operational habits and waste management practices, must also be addressed for effective waste reduction.

Low R^2 values for paper (0.32) and polythene (0.28) waste indicate that non-employee-related factors, including digitalization levels, packaging practices, and staff behavior, significantly influence waste generation. This highlights that interventions targeting staff behavior and operational processes are as important as structural changes, such as installing recycling bins or composting facilities.

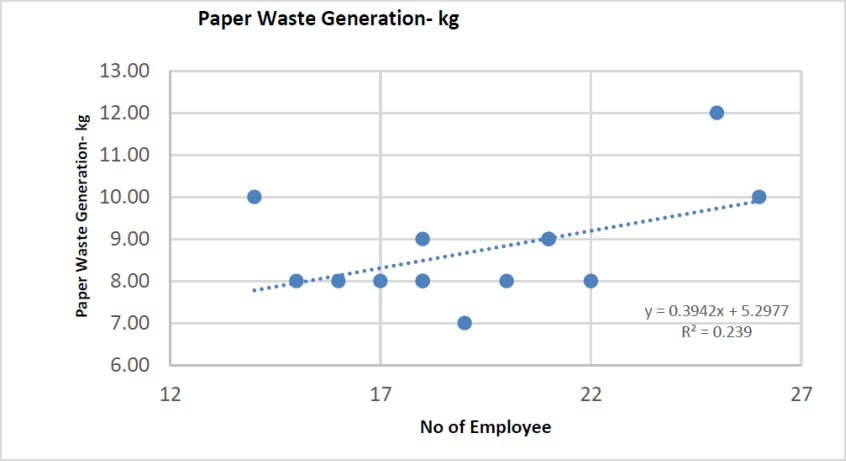


Fig 3. Paper Waste Generation over the number of employees

To address these challenges, the proposed CE framework integrates:

- KPI-based monitoring: Setting branch-level targets to achieve 75% compliance with waste segregation benchmarks.
- Digitalization strategies: Adoption of document management systems (DMS) to reduce paper waste by ≥25% over baseline.

- Periodic review and audits: Self-reporting complemented by independent verification ensures both accuracy and accountability.

These measures ensure that the framework accounts for both technical solutions and human behavioral factors, making waste management practices more robust and scalable across branches.

4.2 Digitalization with Document Management Systems (DMS) and CSR initiatives:

Most banks have adopted digital operations, achieving a 50–70% reduction in paper use, though only 53% use formal DMS systems. In the analysis, 67**%** offer green financing, but only 27% provide customer incentives. CSR engagement in circular economy initiatives remains low at 20%.

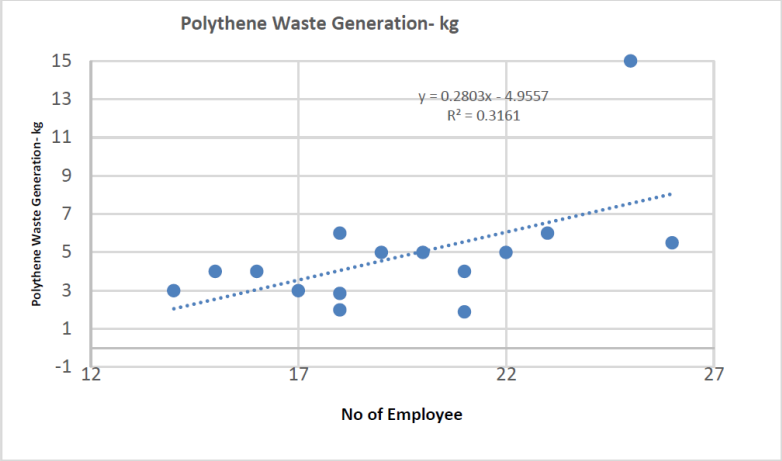


Fig. 4 Polythene Waste Generation over the number of employees

Most branches are aligned toward minimizing paper use, though uniform targets and enforcement strategies could further optimize reduction.

Circular Business Model Practices, including Green Loans and Sustainable Financing Products, are used by 10 of 15 banks in some form of green finance. This is a positive trend, indicating a growing financial commitment to environmental responsibility.

Table 2. Summary of the Digitalization Process

Category	Observation	Recommendation
Digitalization in banking operations (e-statements, e-signatures) in the bank	Fully adopted across all branches	Sustain momentum and upgrade to DMS
Paper Reduction and reduction in physical documentation usage	The majority achieved 60% -70% reduction	Standardize reduction targets and upgrade to DMS
Document Management Systems	Only half use formal systems	Promote bank-wide adoption
Green Financial Products- Green loan or sustainable financing products offered	Adopted by 67% of branches	Promote at all branches
Providing financial incentives for sustainable customer behaviors	Very low at 27%	Develop rewards linked to green actions
Circular CSR Programs	Minimal 20%	Expand outreach and partnerships

4.3 Building Envelope and HVAC Analysis

Most bank branches use 4–6 mm clear or tempered glass windows that do not incorporate low Solar Heat Gain Coefficient (SHGC) glass due to a lack of low-SHGC coating, resulting in higher cooling loads. Wooden frames often exhibit air leakage due to aging and warping, whereas sealed aluminum frames do not. About 53% of branches effectively use natural daylight, while 47% depend entirely on artificial lighting. 60% have concrete slab roofs with minimal infiltration, whereas 40% with Zn/Al or tile roofs show leakage—mainly through poorly sealed service entries. Door infiltration is common across types due to poor sealing and maintenance. Installing Sun Control Window Film on glazed panels can reduce total solar energy by 50%, IR by 97%, and UV by 99%, improving indoor comfort and energy efficiency with a 2.9-year payback period.

HVAC systems operate under typical design conditions (24 °C indoors, 33 °C outdoors, 58% RH), but require better zoning and insulation to maintain efficient performance.

4.4 Key Recommendations for MVAC Efficiency

MVAC systems across bank branches show several efficiency gaps and opportunities for improvement. Key recommendations include upgrading from outdated R22 refrigerant units to R410A or R32 systems. Introducing zone-based temperature controls, occupancy sensors, and IAQ monitoring (CO_2, RH, VOC) is advised, as over 60% of branches lack fresh-air systems, which can lead to poor air quality. Energy-efficient equipment selection is limited, and no Energy Star-rated A/C units were found. Most units are under 6 years old, but maintenance is often below manufacturer standards, leading to reduced efficiency and higher costs.

Condensate water reuse is completely neglected, despite producing 10–20 L/hour per branch, representing a major sustainability opportunity.

Only 50% of branches have a dedicated fresh air supply, and just 20% use CO_2 sensors. Exhaust ventilation exists in only 20% of branches, mostly running continuously without controls, wasting energy.

Overall, branches lack standardized ventilation strategies. Recommended actions include:

- Implement mechanical ventilation with energy recovery,
- Reuse condensate water for landscaping or flushing,
- Install IAQ sensors and occupancy-based controls, and
- Upgrade restroom ventilation with efficient fans and timers to reduce energy use.

4.5 Renewable Energy Utilization

About 60% of branches have installed solar PV systems with capacities of 20–40 kW and 3–4-year payback periods, while 40% have no solar adoption or plans for it. Despite strong rooftop potential and favorable solar conditions in Sri Lanka, renewable energy remains underutilized. The key initiatives required to

- Encourage remaining branches to assess rooftop feasibility.
- Leverage government incentives and net metering for better ROI.
- Integrate battery storage for resilience.
- Use smart meters for monitoring and load optimization.

In addition, no branches currently use biogas systems. However, the availability of biodegradable waste and space makes small-scale biogas plants a viable option for waste-to-energy integration in medium-scale canteen operations.

4.6 Water Efficiency with Benchmark Comparison

According to the Code of Practice – SLS 745 Part 1 (Sri Lanka Standard for Plumbing Installations), the typical water consumption benchmark for office buildings is approximately 55 liters per employee per day. Based on actual data collected from 15 bank branches, the average daily specific water consumption is around 61.7 liters/employee/day.

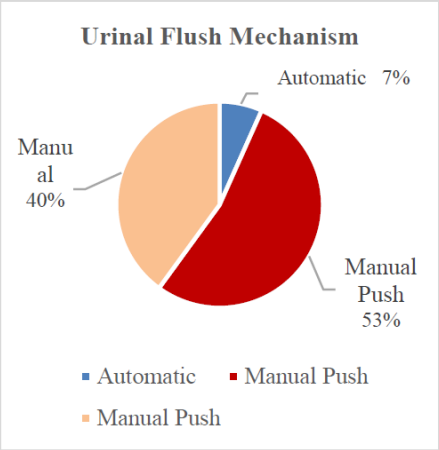


Fig. 5 Urinal Flushing Mechanism

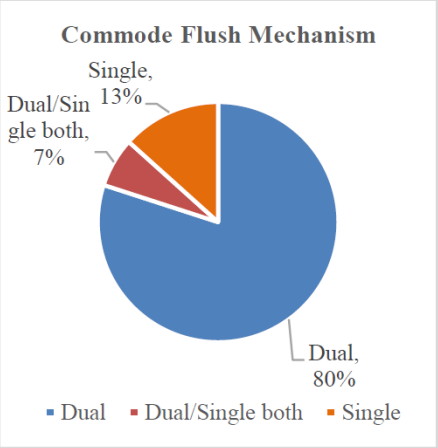


Fig. 6 Commode Flushing Mechanism

- The average consumption is exceeding 12.2% of the national benchmark as per SLS 745. This indicates that many bank branches have room to improve and meet or exceed the national target.
    - The current water consumption trend across surveyed branches indicates promising potential for benchmarking and further optimization with the following recommendations for Water Efficiency Improvements.
- Install low-flow plumbing fixtures (aerators, dual-flush toilets).
- Optimize maintenance to fix leaks and ensure pressure regulation.
- Install submeters to monitor specific zones (restrooms, pantry) for targeted improvements.
- Use water-efficient appliances (e.g., sensor taps, automatic shutoff systems).
- Employee awareness campaigns on water-saving behavior.
- Introducing rainwater harvesting or greywater reuse systems in selected branches

Gradual transition to sensor-based automatic flushing systems is recommended.

- These use preset volumes and flush only when needed, ensuring better water management.
- Dual-flush or flow-rate-controlled valves (in case full automation is not viable due to budget constraints).
- Water audit and retrofit planning under green certification goals or sustainable facilities management policies.

In addition, the banking sector's readiness to embrace circular economic strategies, including Greywater reuse, Rainwater harvesting, water-efficient fixtures, and Smart metering systems, should be reinforced.

Of the 15 bank branches surveyed, only 2 have implemented Rainwater Harvesting (RWH) systems, while the remaining 87% lack them. This indicates significant underutilization of a highly sustainable, cost-effective water management practice within the banking sector. This area is a very tangible, swift win for circular economy integration by reducing water waste, improving hygiene, and aligning with SLS 745 Part 1 or LEED/EDGE certification criteria.

5. Conclusions

The study confirms the feasibility and necessity of implementing a Circular Economy Framework for Sri Lanka's banking sector. Although partial practices exist, the absence of structured CE integration has limited sectoral transformation. The proposed model addresses energy, water, waste, digitalization, procurement, and indoor quality through practical interventions and clear benchmarks, supported by a comprehensive review mechanism.

5.1 Policy and Practice

Energy management:

- Expand solar PV adoption in all the bank premises
- Phase out R22 refrigerant and transition to retrofit with R32 refrigerants with high EER ratio

- Improve HVAC zoning and introduce smart metering in all the branches.
- Retrofit with > 95% efficacy LED lighting system and automatic lighting control systems/ occupancy sensors for corridors and washroom areas.
- Install heat-rejection window films or low-emissivity (Low-E) glass on glazed or tempered glass panels of branches, ATM/SBU cubicles
- Regular Energy audits at branches every 2 years.
- Implementation of the Energy Star Rating System to align with the SLSEA benchmark and evaluate, reward the energy performance of bank branches, and recognition/awards to Branch Managers.

Water Efficiency:

- Enforce low-flow plumbing or flow-rate-controlled valves, automatic urinals, and water-efficient dual-flush retrofit system integration.
- Reuse HVAC condensate water for makeup water/gardening.
- Introduce rainwater harvesting systems for space-available branches and install submeters.
- Introduce Smart Metering Systems.

Waste management:

Established source segregation, composting, and pilot biogas systems, and complied with internal waste management benchmarks.

- Organic Waste: 0.84 kg/employee/week
- Paper Waste: 0.39 kg/employee/week
- Polythene Waste: 0.28 kg/employee/week

Digitalization process:

- Mandate for the use of the Document Management System (DMS).
- Standardized paper reduction meets paper waste target benchmarks.
- Adopt electronic documentation (e-papers)
- Establish a daily monitoring process of print activity.

Procurement process:

- Institutionalize green procurement policies that incorporate life-cycle costing and CE criteria for suppliers.
- Supplier Compliance with Environmental or Circular Economy Criteria Adhere to the bank's Green Procurement Policy

Ventilation and Indoor Air Quality:

- Install CO_2 sensors and IAQ monitoring systems
- Mechanical ventilation with occupancy controls

Review Mechanism

Table 3 Review Mechanism Summary

Mechanism	**Interval**	**Responsible Party**
Progress Reporting	Annually	Regional Operations Managers or the Sustainability /ESG team
KPI Tracking	Ongoing	Sustainability Department
Staff and Customer Feedback	Every 18–24 months	HR and Sustainability/ESG team
Mechanism	**Interval**	**Responsible Party**

Recognition and Incentives	Annually	Corporate Management
Continuous Improvement Cycle	Every 2 Years	Senior Management / Policy Makers
Independent Audit	Every 2 Years	Accredited Third-Party Auditors

CSR and Awareness:

- Launch staff training programs and customer-facing sustainability campaigns focused on CE literacy.

Sustainable Construction:

- Promote the use of local materials and retrofitting practices to reduce transport emissions.

Lifecycle Asset Management:

- Expand use of modular or Demountable Office Furniture, and ensure planned asset replacement cycles are included in the policy.
- Upgrade procurement to prioritize recyclability.
- Adhere to the Recycle policy framework for decommissioned assets

Electric Mobility:

- Install Pilot EV and solar-based charging points at key urban branches.

5.2 Recommendations:

The proposed CE framework and review mechanism demonstrate a structured pathway for banks in Sri Lanka to transition toward sustainable operations. Annual monitoring, KPI tracking, staff/customer engagement, and independent verification ensure continuous improvement and accountability. This approach not only supports compliance with national regulations but also enhances institutional reputation and operational efficiency. The model can be scaled to other service industries in emerging economies, contributing to broader sustainability transitions.

The study demonstrates that, while Sri Lankan banks adopt selective sustainability measures, a holistic CE framework is lacking. Adopting the proposed framework can:

- Reduce energy intensity to meet benchmarks.
- Cut water by >20% through reuse systems.
- Eliminate up to 60% of paper waste through digitalization.
- Improve staff health and productivity via enhanced IEQ.

Policy Recommendations:

- Incentivize renewable energy adoption via subsidies or tax credits.
- Mandate waste segregation and recycling partnerships in banks.
- Introduce sector-specific CE guidelines by the Central Bank of Sri Lanka.
- Expand compliance monitoring for SEC and water efficiency.

5.3 Future Research

Further studies should evaluate the financial payback periods of CE interventions and explore customer behavior towards paperless banking.

- Conduct economic feasibility assessments for CE implementation across different bank types (small-mid- large-high-rise) and throughout all regions in Sri Lanka.
- Track the performance of branches over time after the framework is implemented to assess actual outcomes.
- Develop a sector-specific CE certification for Sri Lankan financial institutions.
- Investigate customer behavior influence on in-branch waste and energy use.
- Study the impact of full digital banking transitions on physical branch energy and resource intensity.

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Powering Sustainability: A Life Cycle Assessment of Household Lithium-Ion Batteries in Sri Lanka

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Abstract: This study conducts a comprehensive Life Cycle Assessment (LCA) of household lithium-ion batteries (LIBs), specifically Lithium Iron Phosphate ($LiFePO_4$) batteries, used in solar energy storage systems in Sri Lanka. The research evaluates environmental impacts across the battery's entire lifecycle, including raw material extraction, manufacturing, transportation, use, and end-of-life disposal, using the ReCiPe2016 and Environmental Footprint 3.1 methodologies. Key impact categories analyzed were Global Warming Potential (GWP), Resource Depletion, Acidification, Marine Eutrophication, and Ozone Depletion. Findings revealed that the usage phase dominates environmental impacts, mainly due to charging-related electricity consumption, with grid dependence on fossil fuels intensifying emissions, resulting in a total of 558.054 kg CO2 eq GWP. Transitioning to renewable energy sources for charging could significantly mitigate these effects. The manufacturing phase is the second-largest contributor, dominated by energy-intensive processes for extracting and processing raw materials such as lithium, copper, and aluminum. Recycling and using secondary materials, such as recycled copper/aluminum, demonstrate notable reductions in resource depletion and emissions, emphasizing the benefits of circular economy practices. The study highlights Sri Lanka's challenges, including limited recycling infrastructure and public awareness, which hinder sustainable end-of-life management. Surveys indicate that 61.3% of respondents face barriers due to inadequate recycling facilities, while 54.8% are aware of the environmental impacts of LIBs. Policy recommendations include promoting the integration of renewable energy, enhancing recycling programs, and incentivizing cleaner production technologies to reduce the environmental footprint of LIBs. This research provides actionable insights for policymakers, manufacturers, and consumers to foster sustainable battery lifecycle management and align with the United Nations Sustainable Development Goals (SDGs).

Keywords: Environment, Eco-friendly, Hotspots, Manufacturing, Niche, Sustainability

1 Introduction

Lithium-ion batteries have become part of our lives in recent years. These batteries include those used in smartphones, laptops, and even in home solar energy storage systems. The demand for these batteries in Sri Lanka has been growing steadily over the years. They are preferred because they are fast, long-lasting, and require minimal care. However, there is a flip side to this rising dependency on lithium-ion batteries. The life cycle, from manufacturing through utilization to ultimate disposal, poses various negative effects on the environment. From the extraction of raw materials used to manufacture batteries to the environmental impacts of disposing of batteries when they are no longer useful, every phase of battery production harms our planet. In Sri Lanka, where we are still struggling to establish waste management systems, understanding how to dispose of old and used batteries is very challenging. Inadequate disposal may cause pollution, harm the quality of our soil and water sources, and threaten the community's health and the environment. Even though lithium-ion batteries are commonly used in Sri Lankan households, we have yet to understand the environmental repercussions, or lack thereof, of these batteries throughout their life cycle. For this reason, one cannot implement appropriate measures and objectives to prevent detrimental impacts on our surroundings. This is a serious problem that will only worsen as the usage of these batteries is expected to increase. That is why this research focuses on a life cycle assessment of household lithium-ion batteries in Sri Lanka to help fill that gap. I will analyze the environmental impacts of the battery life cycle, including raw material acquisition, battery manufacturing, use, and end-of-life management. In other words, the objective is to identify areas for optimization to reduce the environmental impact of these batteries. The findings of this study will be beneficial to policymakers, manufacturers, and, above all, consumers who need to embrace sustainable practices.

In conclusion, this study examines how to foster and adopt new lithium-ion battery technologies while being as accountable for the environmental costs as possible. Studying these impacts will help us develop complete solutions to ensure a sustainable environment for Sri Lanka. The main objective of this study is to conduct a detailed LCA of household lithium-ion batteries in Sri Lanka to assess their life-cycle ecological impacts, from material procurement

for battery manufacturing to end-of-life disposal. This assessment aims to pinpoint critical issues and areas for further improvement, offer practical suggestions to minimize environmental harm, and help establish environmentally friendly WM management practices and policies. Focusing on the raw material extraction, processing, transportation, utilization, and recycling stages associated with these batteries, the study aims to provide a comprehensive picture of their environmental impacts. This analysis will help pinpoint the most critical environmental hotspots and identify areas where appropriate approaches can be employed. The information will be collected from primary and secondary sources. Company data, battery manufacturer data, recycling facilities, government reports, and academic studies will all be included. Through this data analysis, the research will conduct a comprehensive life-cycle assessment (LCA) to determine the environmental impacts at each stage of the battery's life cycle. Stakeholder Engagement: This research will engage stakeholders. Interacting with a wide variety of stakeholders (e.g., manufacturers, consumers, policymakers, and environmental groups) is likely to provide useful feedback and validation of findings. The research will also involve a literature review of existing policies and regulations of lithium-ion batteries in Sri Lanka.

2 Literature Background

The growing demand for lithium-ion batteries (LIBs) across diverse applications, from electric vehicles to residential energy storage, coupled with the significant energy consumption associated with their use, underscores the need to understand the impacts of LIB use on environmental quality. Examining all three points of impact (production, use, and end-of-life) for batteries requires a life-cycle assessment (LCA), which is crucial for determining their environmental impact. The mining of raw materials for LIBs—namely, lithium, cobalt, and nickel—leaves behind hefty ecological footprints. Mining involves energy-intensive processes that often destroy habitats and lead to pollution. For example, the study by Longo et al. on sodium nickel chloride (Na/NiCl2) batteries attributed 60% of the overall environmental impact to the manufacturing process; a substantial portion of the burden results from raw material extraction. Lithium is extracted mostly from brine and hard rock mining, both of which pose major ecological problems, including water use in dry regions and chemical pollution [1]. This phase involves manufacturing battery cells, which, in itself, consumes a significant amount of energy. Dai et al. investigated the energy and greenhouse gas emissions of lithium-nickel-manganese-cobalt oxide (NMC) batteries. They concluded that the cathode material (active parts) and the energy during cell production are the main contributors to the impact [2]. Similarly, Ellingsen et al. quantitatively analyzed the energy requirements of the manufacturing stage. They argued that the use of renewable primary energy resources plays a key role in reducing overall impacts [3]. The production of cathode and anode materials, cell assembly, and electrolyte incorporation are all significantly energy-intensive. Sarre et al. described these aging and degradation mechanisms in lithium-ion batteries, demonstrating that reactions between active materials and electrolytes at electrode interfaces are a major contributor to energy and power losses over time [4]. As degradation compromises battery performance and lifespan, second-life applications and recycling should be pursued to extend battery life and minimize the environmental footprint. The formation of a solid electrolyte interphase (SEI) on the anode, electrolyte decomposition, and structural transformations of the cathode material are among the other factors contributing to the degradation. The substantial environmental benefits of the direct cathode recycling process over hydrometallurgical and pyrometallurgical methods in automotive LIB recycling were also demonstrated in a comparative LCA study [5]. Moreover, they can be given a second life in applications such as stationary energy storage systems, thereby prolonging their productive life and enhancing sustainability. This enables second-life batteries to be used in less demanding applications, such as energy storage solutions, at a fraction of the cost. Comparative Recycling Methods: Recycling processes also have differential environmental impacts. The study by Hiremath et al. revealed that while pyrometallurgical, hydrometallurgical, and direct cathode recycling methods are viable, direct cathode recycling is environmentally sustainable [6]. Longo et al. demonstrated that Na/NiCl2 batteries are, to some extent, more environmentally friendly than lithium-ion batteries in certain applications, with lower CED and GWP [1]. In the same context, Marques et al. conducted a cradle-to-gate LCA of LiFePO4 and LiMn2O4 batteries, noting that although LiFePO4 batteries had higher functional performance than LiMn2O4 batteries, they had a greater impact during manufacturing [7]. Zackrisson et al. conducted an LCA of lithium-air batteries and concluded that they could have up to 10 times the energy density of current LIBs. However, these technologies are accompanied by issues such as electrolyte stability, charging and discharging efficiency, and overall cell lifespan [8]. In the same vein, sodium-ion batteries have the potential to use more readily available raw materials and to have significantly lower environmental impacts during extraction and processing than lithium-based systems. Studies conducted in Europe, such as those by Ellingsen et al. and Grimsmo et al. (2017), present regional life-cycle impact results and highlight the importance of local context in LCA [9] [10]. For example, using renewable energy to charge batteries in regions with a robust green energy grid can significantly improve the overall sustainability of LIBs. LIBs' second-life applications are relevant because they improve battery-operation sustainability and reduce long-term environmental impact. Richa et al.

highlighted the viability of recovering and reusing dormant electric vehicle batteries and integrating them into home energy storage systems [11]. This method also eliminates waste while addressing the costly challenge of energy storage. Among the various factors that influence the performance and durability of LIBs, aging and degradation are key issues. This aging process involves the formation of the solid electrolyte interphase at the anode, further electrochemical decomposition of the electrolyte, and, lastly, changes in the structure of the cathode material [4]. As a result of electrode material degradation, the battery experiences capacity fade and an increase in its inherent internal resistance. Therefore, the battery's overall utility, usefulness, and total lifetime are reduced. It will also investigate how LIBs age, develop methods to mitigate degradation over their lifetime, and ascertain failure modes. Second-life applications of LIBs pose another concern, as their performance warrants study. Indeed, the viability of batteries used in second-life applications has been confirmed in various academic studies, as they may have lower capacity and performance than newly built batteries. However, they can still be effectively used in certain applications. For instance, Neubauer et al. reported that decommissioned EV batteries could be optimally used in home energy storage systems to reduce costs and environmental impacts [12]. Three recycling processes for automotive LIBs were investigated: hydrometallurgical, pyrometallurgical, and direct cathode recycling [5]. The study found that direct cathode recycling is the most environmentally friendly approach, as it efficiently recovers valuable materials and reduces the overall environmental burden of LIBs. This method uses less energy than hydrometallurgical recycling, which involves leaching metals from shredded batteries, or pyrometallurgical recycling, which uses high heat to separate metals. Environmental Benefits of Recycling: Recycling end-of-life LIBs benefits the environment by recovering valuable materials and reducing the use of virgin materials. Hiremath et al. highlighted the role of recycling in the reduction of life cycle environmental impacts of LIBs, pointing out that by recycling, one can evade10-30% of the impacts occasioned by production [6].

3 Methodology

Lithium-ion batteries for solar storage are chosen to highlight their importance in facilitating the adoption of renewable energy, particularly in Sri Lanka, where solar energy is rapidly taking off. I have decided to focus on solar storage lithium-ion batteries. Solar storage systems use lithium-ion batteries to store excess energy produced during the day, then release it later at night or when the sun is down. As with any technology, their superior energy density, longer lifespan, and deeper depth of discharge make them much more efficient and cost-effective over time than traditional storage technologies like lead-acid batteries. In line with its goal of improving energy security in areas with precarious grid connectivity, they offer lithium-ion solar storage batteries as an additional benefit to address the localized challenges of decentralized energy systems. This makes it technically and environmentally relevant for the study.

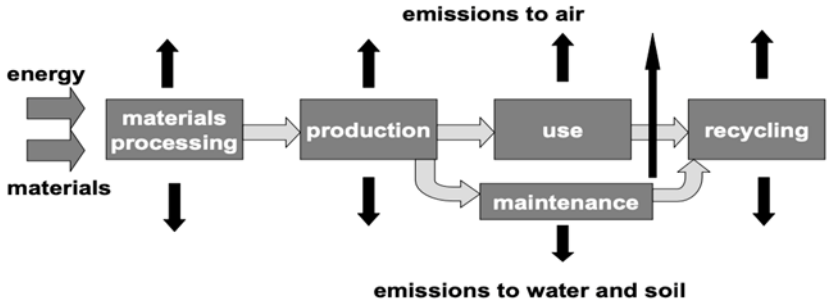


Fig. 1 LCA model

3.1 The Functional Unit Definition

1kWh of battery capacity used daily for 10 years. This is a standard in battery-related Life Cycle Assessments (LCA), so 1 kWh of battery capacity was chosen as the functional unit, as it can be easily scaled and applied to larger systems. Moreover, in industry, modular battery designs are common, with each module having a fixed capacity, such as 1 kWh. This modularity enables evaluation of environmental impacts per kWh and makes the analysis comparable to, yet relevant to, other technologies, such as lead-acid batteries. The chosen operational period was 10 years, which aligns with the expected lifetime of lithium-ion batteries (solar storage) under normal use. With high durability and long cycle life, these batteries deliver approximately 3,000–5,000 charge/discharge cycles with little capacity degradation. During this time, the battery cycles around 3,650 times, which matches its design specs. In addition, the 10-year time horizon

facilitates consideration of cumulative environmental impacts, such as charging energy inputs, and highlights the importance of battery durability in reducing the long-term burden. This time frame aligns with industry norms and global practice and also highlights economic feasibility. The chemical composition of solar storage lithium-ion batteries is Lithium Iron Phosphate (LiFePO4).

3.2 Methods of Data Collection

Surveys and Questionnaires - Conduct surveys of households using lithium-ion batteries to establish their usage, charging, and disposal methods. Conduct surveys of battery manufacturers, distributors, and recyclers to collect data on production processes, materials, energy use, and disposal practices. Academic Reports and LCA Databases - Search for academic sources, such as peer-reviewed journal articles, conference proceedings, and dissertations, reporting on materials that focus on the life cycle assessment of lithium-ion batteries and similar technologies. Refer to research papers of international organizations, environmental campaigning groups, and industry governing bodies that outline the battery life, environmental footprint, and recycling technologies. Since part of this study focuses on environmental impacts at specific life-cycle stages, we use online LCA databases such as Ecoinvent, GREET, and the US LCI Database. Government and International Databases: Government organizations such as the Environmental Protection Agency (EPA) and international organizations such as the International Energy Agency (IEA) and the United Nations Environment Program (UNEP), as well as various departments of the Country in question, may be used to access the data. Data from Industry and Policy Agencies - Gather data from battery manufacturers to acquire current information on the types and amounts of raw materials used, energy used during production, and emissions made by the manufacturing process. Gather information from retail stores and wholesalers regarding the categories of lithium-ion batteries installed within homes. The paper stated that the study aimed to collect data from various sources to enrich it and provide valid information.

3.3 The IDEMAT

Excel sheet was used as a primary tool for determining impact factors of metals for such elements as lithium carbonate, graphite, aluminum, copper, and so on. These data provided necessary values for several impact categories, such as GWP, Resource Depletion, Acidification, and Eutrophication, which served as the basis for LCA computations. Data from battery manufacturers and recyclers helped to understand their current practices and preferences regarding battery production, transportation, composition, and disposal. These inputs helped fine-tune the study's focus and confirm that the collected data reflected actual practice. International shipping modes and distances, as well as domestic Sri Lankan Road transport characteristics, were collected with reference to other recognized logistics data. Further, the study included localized data on Sri Lanka, including the electricity grid mix and emissions during the battery's use phase. Another method involved conducting surveys to determine general disposal behaviors and battery recycling projects, to avoid overlooking regional differences. Using information from various sources, the study ensured that the environmental effects of lithium-ion batteries were thoroughly assessed at each life-cycle stage. The Life Cycle Assessment (LCA) framework was developed to systematically account for the environmental impacts of lithium-ion batteries throughout their lifecycle. Within a cradle-to-grave system boundary, the analysis included raw material extraction, manufacturing, transportation, use, and end-of-life. This approach allows environmental impacts to be evaluated. The IDEMAT Excel sheet integrates several databases. This database provides data on ReCiPe2016, carbon footprint, CED, and environmental footprint 3.1. Environmental impact factors for materials and processes were obtained using the IDEMAT Excel sheet as a primary source. Material and process quantities were multiplied by impact factors for the categories of Global Warming Potential (GWP), Resource Depletion, Acidification, and Eutrophication. For example, IDEMAT data were used to quantify the environmental burdens of materials such as lithium carbonate, graphite, copper, and aluminum. Aggregated values were then calculated for the total environmental impacts of each route stage. Transparency was maintained in the analysis by documenting substitutions and assumptions for materials not included in IDEMAT.

3.4 ReCiPe2016

ReCiPe2016, commonly used to convert inventory data, such as emissions and resource extraction, into environmental impact indicators, is a Life Cycle Impact Assessment (LCIA) method. It is structured into three levels: single-score values, midpoint indicators, and endpoint indicators. Midpoint indicators assess specific environmental problems (e.g., climate change or eutrophication), while endpoint indicators indicate broader impacts on human health, ecosystems, and resource availability. All impacts are aggregated into a single metric for simple comparison, yielding a single score. ReCiPe2016 is evaluated at the midpoint level, focusing on individual impact categories, and at the endpoint level by aggregating damage within underlying systems. The impact categories considered are wide-ranging. They also include: global warming potential, which measures the contribution of pesticides' greenhouse gas emissions to climate change;

ozone depletion, which considers the effects of substances such as CFCs on the ozone layer; and acidification, which assesses emissions that cause acidification of soil and water. The chapter also discusses eutrophication, describing the harmful effects of nutrient enrichment on marine and terrestrial ecosystems, as well as the human and ecological toxicity associated with chemical exposure. This is further expanded to include categories of resource depletion (fossil and mineral resources) and photochemical ozone formation from ground-level ozone emissions, water consumption impacts on freshwater availability, and ionizing radiation effects on human health. ReCiPe2016 addresses damage to human health, ecosystems, and resource availability at the endpoint level. It accounts for impacts on human health, including climate change-related effects and exposure to toxic substances. It evaluates biodiversity loss resulting from land-use change and ecosystem acidification. A second aspect of resource availability assesses the depletion of non-renewable resources and relates to a possible scarcity of resources for subsequent generations. As a comprehensive framework for environmental impact assessment, ReCiPe2016 is robust and flexible, allowing it to focus on selected categories or integrate them into broader endpoint indicators to assess the sustainability of products and systems across different lifecycle stages.

3.5 Environmental Footprint 3.1

The Environmental Footprint 3.1 EF 3.1 method is a standardized Life Cycle Impact Assessment (LCIA) method used by the European Commission to assess the environmental performance of products, organizations, and services. It has been selected for its life-cycle approach and comprehensive set of impact categories to address a variety of environmental issues. Midpoint indicators are widely used for regulatory purposes, sustainability assessments, and product environmental footprint (PEF) initiatives; EF 3.1 focuses on midpoint indicators. It aims to align environmental assessment across industries by developing consistency, comparability, and scientific robustness in environmental impact evaluation. EF 3.1 covers a wide range of impact categories. It is used to evaluate climate change by measuring how greenhouse gas emissions contribute to global warming and ozone depletion, the depletion of the stratospheric ozone layer caused by substances such as chlorofluorocarbons. Impacts of sulfur dioxide and nitrogen oxide emissions on soil and water acidification are assessed. Terrestrial, freshwater, and marine categories of eutrophication are analyzed to assess the impacts of nutrient emissions (nitrogen and phosphorus). The method also analyzes photochemical ozone formation, the creation of ground-level ozone that harms human health and ecosystems. Substances on humans and freshwater ecosystems. The depletion of fossil fuels and non-renewable minerals is assessed, as is the extent of water use and its environmental impact. Soil quality and biodiversity loss impacts from land use are quantified, and the potential harm of ionizing radiation to human health is assessed. The EF 3.1 method provides a framework for comprehensive, standardized environmental impact evaluation and is a valuable tool for assessing environmental products, systems, and services. Focusing on midpoint indicators enables detailed analysis of specific environmental processes without compromising consistency and facilitates comparative discussion across industries and regions. Affected are human toxicity and ecotoxicity, and portray the harmful effects of toxic

3.6 Calculations

Expected number of cycles of the battery:

$$Expected\ number\ of\ cycles = 10\ years\ lifespan\ for\ 365\frac{days}{year}$$

$$= 10 \times 365 = 3650 cycles$$

Functional Unit Calculations

Generally, the specific energy of Lithium Iron Phosphate (LiFePO4) batteries ranges from 90 to 160 Wh/kg. For calculation purposes, the average of the range was taken.

$$Specific\ Energy = \frac{160 + 90}{2} = 125 Wh/kg$$

$$Weight\ for\ 1kWh = \frac{1kWh}{125wh/kg} = \frac{1000Wh}{125Wh/kg} = 8kg$$

Weight of each component per functional unit

Table 1: Percentage by weight of battery components

Component	Percentage by weight	Actual weight (kg)
Cathode	40%	0.4 x 8 = 3.2
Anode	25%	2.0
Electrolyte	10%	0.8
Separator	5%	0.4
Anode collector	10%	0.8
Cathode collector	10%	0.8

The cathode is LiFePO4, the anode is graphite, the electrolyte is Lithium hexafluorophosphate in organic solvents, the separator is polyethylene, the anode collector is copper, and the cathode collector is aluminum. The cathode in the LiFePO4 should be LiFePO4. Because of its excellent lithium-ion intercalation properties, abundance, and relatively low cost, graphite is the most widely used anode material in lithium-ion batteries. Lithium hexafluorophosphate ($LiPF_6$) and carbonate-based organic solvents (usually ethylene carbonate) are the industry-standard electrolyte components for lithium-ion batteries, providing high ionic conductivity and stability. Most separators are either polyethylene or polypropylene. They are thin, highly porous, unable to short-circuit, and yet allow ion flow. Copper and aluminum are universally used as anode and cathode collectors, respectively. They comprise a typical, well-documented configuration of $LiFePO_4$ lithium-ion batteries, which is why they were chosen for the study. This aligns with mainstream industry practice and has been referenced in LCA studies and other technical literature on LiFePO4 batteries.

Since no data on battery distribution distances within Sri Lanka are available, the distances covered were calculated based on assumptions. The distances from Sri Lanka's capital (Colombo) to each district were summed and assumed to represent the distribution distance of batteries within Sri Lanka. It was also assumed that these distances would cover battery distribution within each district, since battery distributors would not deliver to each district from Colombo. Although the distribution starts from Colombo, they are distributed from district to district (from the nearest district)

Table 2: Battery Distribution within Sri Lanka

District	Distance from Colombo (km)
Gampaha	27.9
Kaluthara	44.0
Kuruneagala	92.1
Puttalam	136
Kegalle	77
Ratnapura	83.7
Kandy	120
Matale	143
Nuwaraeliya	158
Badulla	210

Monaragala	258
Galle	130
Matara	161
Hambantota	242
Ampara	306
Batticaloa	312
Anuradhapura	195
Polonnaruwa	220
Trincomalee	255
Vavuniya	250
Kilinochchi	329
Mannar	311
Jaffna	389
Mullaitivu	325
Total	**4774.7**

4 Results and Discussion

4.1 Results from the IDEMAT Excel Sheet on Impact Categories

The uncertainty rubric was set at 10% for a perfect database match, 30% for a plausible substitution, and 100% for a guess. Two options, A and B, were analyzed with the given boundaries.

- Option A: Using Virgin copper and aluminum (primary)
- Option B: Using secondary copper and aluminum (Virgin + recycled)
- Impact Unit - kg CO2 eq. Boundaries – Cradle to Grave

4.1.1 Carbon Footprint (Global Warming Potential – GWP)

Manufacturing		Eco-Intensity (impacts/kg)	Mass per Item (kg)	Items per func.unit (#)	Uncertainty %	Notes	Calculated Impact
	LiFePO4 Lithium Iron Phosphate	8.799990	3.2	1	10%		28.159969
	Graphite for Batteries	9.152295	2	1	10%		18.304589
	Ethylene Carbonate Organic Solvent	2.500000	0.72	1	30%		1.8
	LiPF6 Lithium Hexaflourophosphate	8.000000	0.08	1	30%		0.64
	bio-PE (Polyethylene) not biodegradable	1.870000	0.4	1	10%		0.748
	Copper (Primary)	4.190966	0.8	1	10%		3.3527729
	Aluminum (Primary)	8.678567	0.8	1	10%		6.9428535
							0
							0
							0
							0
							0
							0
							0
							0
							0
							0

Transport		Eco-Intensity (impacts/ ton-km)	Mass per Item (ton)	Distance per Item (km)	Items per func.unit (#)	Uncertainty %	Notes	Calculated Impact
	Ocean Freight	0.004775	0.008	8800	1	10%		0.3361889
	Truck+Container	0.076041	0.008	4700	1	30%		2.8591427
								0
								0

Use		Eco-Intensity (impacts/MJ or other)	Amount per Item (MJ or other)	Items per func.unit (#)	Uncertainty %	Notes	Calculated Impact
	Electricity Sri Lanka Production	0.152892	365	10	10%		558.05404
	Electricity Sri Lanka Production						0

End of Life		Eco-Intensity (impacts/kg)	Mass per Item (kg)	Items per func.unit (#)	Uncertainty %	Notes	Calculated Impact
	LiFePO4 Lithium Iron Phosphate	0.000000	3.2	1	10%		0
	Graphite for Batteries	0.000000	2	1	10%		0
	Ethylene Carbonate Organic Solvent	2.241000	0.72	1	10%		1.61352
	LiPF6 Lithium Hexaflourophosphate	0.000000	0.08	1	10%		0
	bio-PE (Polyethylene) not biodegradable	0.000000	0.4	1	10%		0
	Copper (Primary)	0.000000	0.8	1	10%		0
	Aluminum (Primary)	0.000000	0.8	1	10%		0

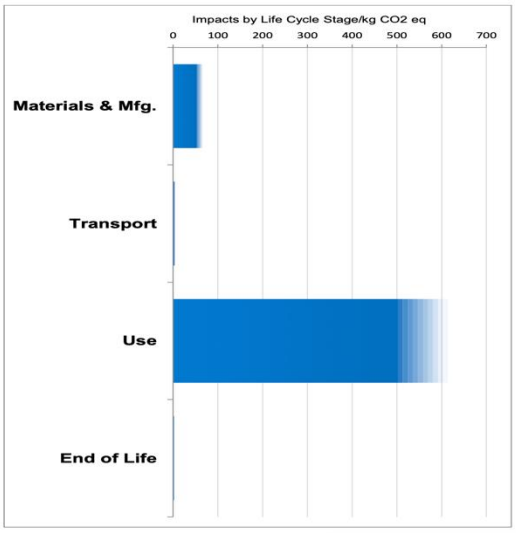


Fig. 2 Carbon Footprint (GWP) impacts of each phase -Option A

Manufacturing		Eco-Intensity (impacts/kg)	Mass per Item (kg)	Items per func.unit (#)	Uncertainty %	Notes	Calculated Impact
	LiFePO4 Lithium Iron Phosphate	8.799990	3.2	1	10%		28.159969
	Graphite for Batteries	9.152295	2	1	10%		18.304589
	Ethylene Carbonate Organic Solvent	2.500000	0.72	1	30%		1.8
	LiPF6 Lithium Hexaflourophosphate	8.000000	0.08	1	30%		0.64
	bio-PE (Polyethylene) not biodegradable	1.870000	0.4	1	10%		0.748
	Copper (Secondary)	0.803982	0.8	1	10%		0.6431857
	Aluminum (Secondary)	0.852752	0.8	1	10%		0.6822019

Transport		Eco-Intensity (impacts/ ton-km)	Mass per Item (ton)	Distance per Item (km)	Items per func.unit (#)	Uncertainty %	Notes	Calculated Impact
	Ocean Freight	0.004775	0.008	8800	1	10%		0.3361889
	Truck+Container	0.076041	0.008	4700	1	30%		2.8591427

Use		Eco-Intensity	Amount per Item	Items per func.unit (#)	Uncertainty %	Notes	Calculated Impact
	Electricity Sri Lanka Production	0.152892	365	10	10%		558.05404
							0
							0

End of Life		Eco-Intensity (impacts/kg)	Mass per Item (kg)	Items per func.unit (#)	Uncertainty %	Notes	Calculated Impact
	LiFePO4 Lithium Iron Phosphate	0.000000	3.2	1	10%		0
	Graphite for Batteries	0.000000	2	1	10%		0
	Ethylene Carbonate Organic Solvent	2.241000	0.72	1	10%		1.61352
	LiPF6 Lithium Hexaflourophosphate	0.000000	0.08	1	10%		0
	bio-PE (Polyethylene) not biodegradable	0.000000	0.4	1	10%		0
	Copper (Secondary)	0.000000	0.8	1	10%		0
	Aluminum (Secondary)	0.000000	0.8	1	10%		0

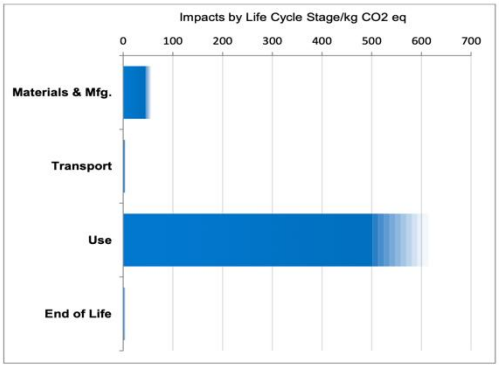


Fig. 3 Carbon Footprint (GWP) impacts of each phase – Option B

The energy-intensive processes required to extract and refine primary copper and aluminum on an industrial scale yield considerable downstream greenhouse gas emissions and other environmental burdens. Recycling these metals eliminates the need to obtain raw materials and reduces overall energy consumption and, in turn, emissions. While the two differences might seem small in this graph, incorporating recycled materials aligns with sustainability principles and reduces resource depletion and the ecological burden of battery manufacturing. It continues this comparison by highlighting how integrating recycled materials into the manufacturing process can eliminate the environmental impacts associated with producing primary materials. Beyond this, promoting the use of recycled metals to reduce the environmental burden of lithium-ion battery systems and enhancing their availability can also be pursued.

4.1.2 ReCiPe2016 Resources (Resource Depletion)

Manufacturing		Eco-intensity (impacts/kg)	Mass per item (kg)	Items per func.unit (#)	Uncertainty %	Notes	Calculated Impact
	LiFePO4 Lithium Iron Phosphate	0.005224	3.20	1	10%		0.0167177
	Graphite for Batteries	0.004236	2.00	1	10%		0.0084721
	Ethylene Carbonate Organic Solvent	0.002164	0.72	1	30%		0.0015581
	LiPF6 Lithium Hexafluorophosphate	0.000000	0.08	1	100%		0
	bio-PE (Polyethylene) not biodegradable	0.003403	0.40	1	10%		0.0013611
	Copper (Primary)	0.003616	0.80	1	10%		0.0028924
	Aluminum (Primary)	0.003222	0.80	1	10%		0.002578

Transport		Eco-intensity (impacts/ ton-km)	Mass per item (ton)	Distance per item (km)	Items per func.unit (#)	Uncertainty %	Notes	Calculated Impact
	Ocean Freight	0.000004	0.008	8800	1	10%		0.0002892
	Truck+Container	0.000073	0.008	4700	1	30%		0.0027364

Use		Eco-intensity (impacts/MJ or other)	Amount per item (MJ or other)	Items per func.unit (#)	Uncertainty %	Notes	Calculated Impact
	Electricity Sri Lanka Production	0.000081	365	10	10%		0.2972492
	Electricity Sri Lanka Production						0

End of Life		Eco-intensity (impacts/kg)	Mass per item (kg)	Items per func.unit (#)	Uncertainty %	Notes	Calculated Impact
	LiFePO4 Lithium Iron Phosphate	0.000000	3.2	1	10%		0
	Graphite for Batteries	0.000000	2	1	10%		0
	Ethylene Carbonate Organic Solvent	0.000000	0.72	1	10%		0
	LiPF6 Lithium Hexafluorophosphate	0.000000	0.08	1	10%		0
	bio-PE (Polyethylene) not biodegradable	0.000000	0.4	1	10%		0
	Copper (Primary)	0.000000	0.8	1	10%		0
	Aluminum (Primary)	0.000000	0.8	1	10%		0

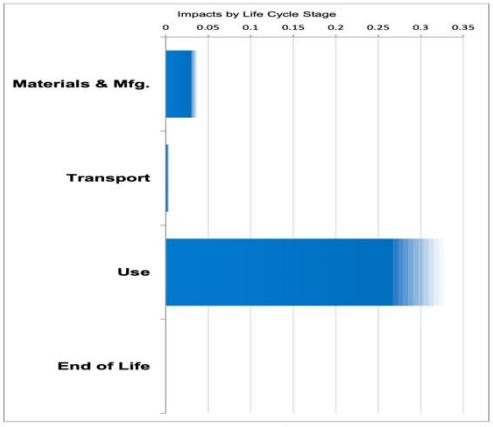


Fig. 4 Resource depletion impacts of each phase – Option A

Manufacturing		Eco-Intensity (impacts/kg)	Mass per Item (kg)	Items per func.unit (#)	Uncertainty %	Notes	Calculated Impact
	LiFePO4 Lithium Iron Phosphate	0.005224	3.2	1	10%		0.0167177
	Graphite for Batteries	0.004236	2	1	10%		0.0084721
	Ethylene Carbonate Organic Solvent	0.002164	0.72	1	30%		0.0015581
	LiPF6 Lithium Hexafluorophosphate	0.000000	0.08	1	100%		0
	bio-PE (Polyethylene) not biodegradable	0.003403	0.4	1	10%		0.0013611
	Copper (Secondary)	0.000254	0.8	1	10%		0.0002029
	Aluminum (Secondary)	0.000604	0.8	1	10%		0.0004833
Transport		**Eco-Intensity (impacts/ ton-km)**	**Mass per Item (ton)**	**Distance per Item (km)**	**Items per func.unit (#)**	**Uncertainty %**	**Notes**	**Calculated Impact**
	Ocean Freight	0.000004	0.008	8800	1	10%		0.0002892
	Truck+Container	0.000073	0.008	4700	1	30%		0.0027364
Use		**Eco-Intensity**	**Amount per Item**		**Items per func.unit (#)**	**Uncertainty %**	**Notes**	**Calculated Impact**
	Electricity Sri Lanka Production	0.000081	365		10	10%		0.2972492
								0
								0
End of Life		**Eco-Intensity (impacts/kg)**	**Mass per Item (kg)**	**Items per func.unit (#)**	**Uncertainty %**	**Notes**	**Calculated Impact**
	LiFePO4 Lithium Iron Phosphate	0.000000	3.2	1	10%		0
	Graphite for Batteries	0.000000	2	1	10%		0
	Ethylene Carbonate Organic Solvent	0.000000	0.72	1	10%		0
	LiPF6 Lithium Hexafluorophosphate	0.000000	0.08	1	10%		0
	bio-PE (Polyethylene) not biodegradable	0.000000	0.4	1	10%		0
	Copper (Secondary)	0.000000	0.8	1	10%		0
	Aluminum (Secondary)	0.000000	0.8	1	10%		0

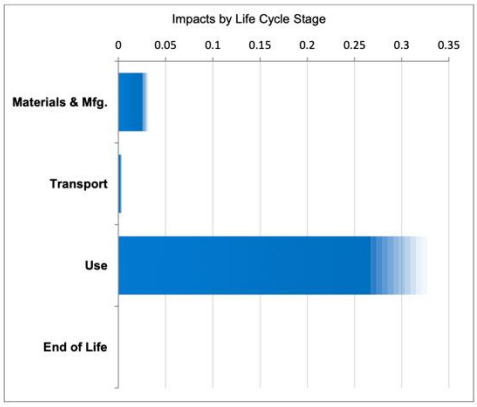


Fig. 5 Resource depletion impacts of each phase – Option B

As evaluated using the ReCiPe 2016 Resource Depletion method. By incorporating recycled materials into their production process, Option B shows a slightly lower total impact than Option A, with the added environmental benefits.

As methods for primary copper and aluminum production demonstrate, most depletion of nonrenewable mineral resources occurs during energy-intensive extraction and refining processes. That is when using recycled copper and aluminum eliminates the need to extract raw materials, significantly reducing the impact of resource depletion. Recycling also requires less energy and uses materials that have already been extracted, putting less strain on resources. Although the two options are quite close, the continual reduction in impacts for Option B underscores the importance of incorporating recycled materials into the manufacturing process to reduce reliance on virgin materials and improve resource efficiency. These findings align with a circular economy philosophy, in which recycling and reuse are favored to minimize environmental impacts. Reuse of these sources can also be promoted in lithium-ion battery production by minimizing resource depletion and expanding sustainable manufacturing practices.

4.1.3 EF3.1 Acidification. (Acidification)

Based on the Environmental Footprint 3.1 Acidification method, the total acidification impacts of Option B, which includes recycled copper and aluminum, are compared with those of Option A, which uses primary copper and aluminum. The results in this thesis show that recycling materials in batteries makes Option B have a slightly smaller total acidification impact than Option A, thereby offering environmental advantages from recycling mature materials in battery production. Lower acidification impacts in Option B are attributed to smaller emissions of sulfur dioxide (SO_2) and nitrogen oxides (NO_x) from 57metals in the recycled metals compared to the production of primary metals. Mining and smelting processes for primary copper and aluminum extraction and refining emit many acidifying pollutants. In contrast, recycling skips the mining stage and uses a less energy-intensive processing route, thereby reducing total emissions and acidification potential. While the impact differences between the two options

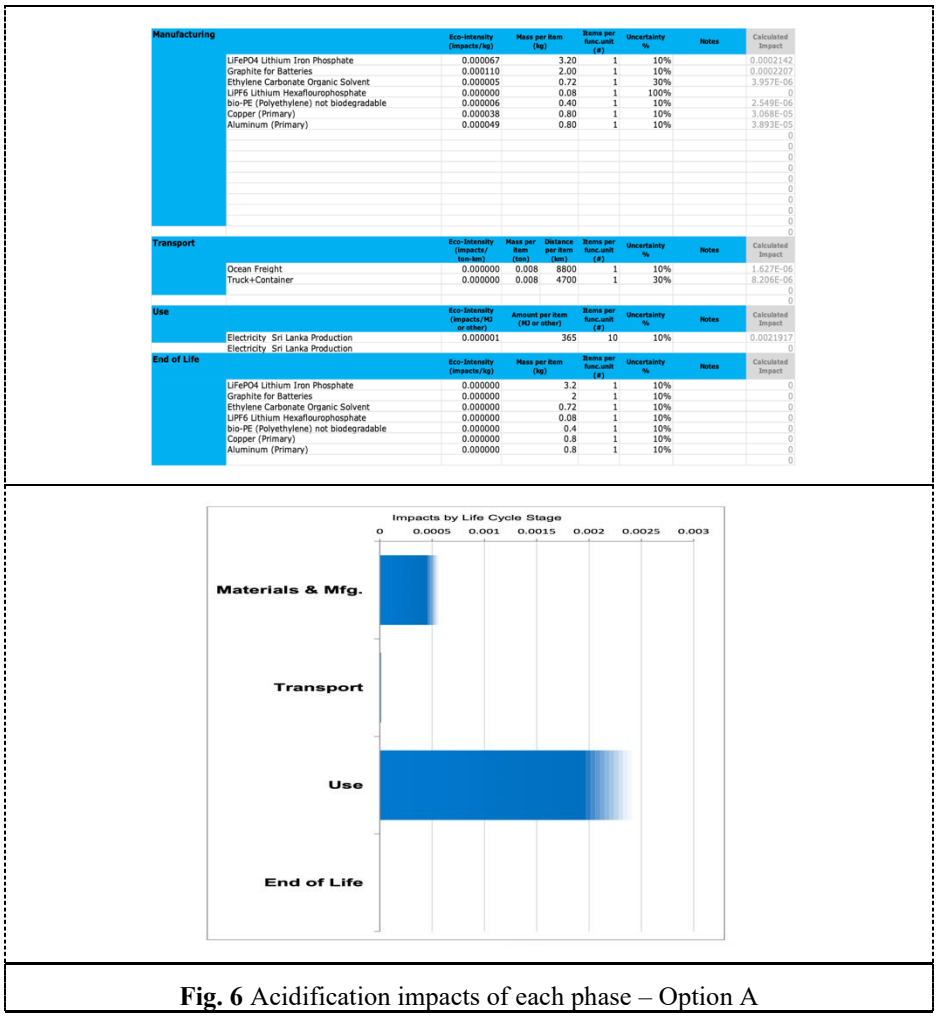


Fig. 6 Acidification impacts of each phase – Option A

They are not great; the ongoing reduction in impact for Option B demonstrates the value of incorporating recycled materials to mitigate acidification. This aligns with the sustainability goals of reducing the exploitation of virgin materials and the associated environmental burdens. Recycling of metals helps reduce acidification potential and also supports broader environmental goals, including resource conservation and energy efficiency.

Manufacturing		**Eco-intensity (impacts/kg)**	**Mass per item (kg)**	**Items per func.unit (#)**	**Uncertainty %**	**Notes**	**Calculated Impact**
	LiFePO4 Lithium Iron Phosphate	0.000067	3.2	1	10%		0.0002142
	Graphite for Batteries	0.000110	2	1	10%		0.0002207
	Ethylene Carbonate Organic Solvent	0.000005	0.72	1	30%		3.957E-06
	LiPF6 Lithium Hexafluorophosphate	0.000000	0.08	1	100%		0
	bio-PE (Polyethylene) not biodegradable	0.000006	0.4	1	10%		2.549E-06
	Copper (Secondary)	0.000001	0.8	1	10%		1.117E-06
	Aluminum (Secondary)	0.000001	0.8	1	10%		8.404E-07
Transport		**Eco-Intensity (impacts/ ton-km)**	**Mass per item (ton)**	**Distance per item (km)**	**Items per func.unit (#)**	**Uncertainty %**	**Notes**	**Calculated Impact**
	Ocean Freight	0.000000	0.008	8800	1	10%		1.627E-06
	Truck+Container	0.000000	0.008	4700	1	30%		8.206E-06
Use		**Eco-Intensity**	**Amount per item**		**Items per func.unit (#)**	**Uncertainty %**	**Notes**	**Calculated Impact**
	Electricity Sri Lanka Production	0.000001	365		10	10%		0.0021917
								0
								0
End of Life		**Eco-Intensity (impacts/kg)**	**Mass per item (kg)**		**Items per func.unit (#)**	**Uncertainty %**	**Notes**	**Calculated Impact**
	LiFePO4 Lithium Iron Phosphate	0.000000	3.2		1	10%		0
	Graphite for Batteries	0.000000	2		1	10%		0
	Ethylene Carbonate Organic Solvent	0.000000	0.72		1	10%		0
	LiPF6 Lithium Hexafluorophosphate	0.000000	0.08		1	10%		0
	bio-PE (Polyethylene) not biodegradable	0.000000	0.4		1	10%		0
	Copper (Secondary)	0.000000	0.8		1	10%		0
	Aluminum (Secondary)	0.000000	0.8		1	10%		0

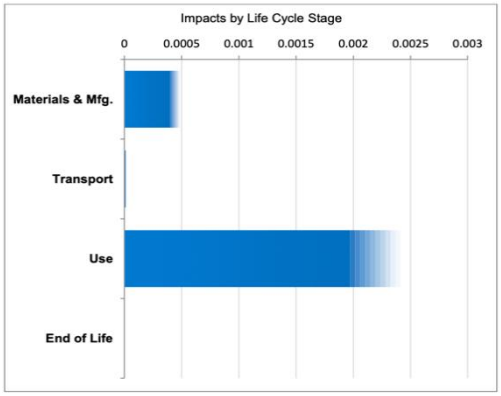


Fig. 7 Acidification impacts of each phase – Option B

4.1.4 EF3.1 Ozone Depletion. (Ozone Depletion)

Manufacturing		Eco-intensity (impacts/kg)	Mass per item (kg)	Items per func.unit (#)	Uncertainty %	Notes	Calculated Impact
	LiFePO4 Lithium Iron Phosphate	3.74E-07	3.20	1	10%		1.198E-06
	Graphite for Batteries	5.32E-09	2.00	1	10%		1.065E-08
	Ethylene Carbonate Organic Solvent	0.00E+00	0.72	1	30%		0
	LiPF6 Lithium Hexafluorophosphate	0.00E+00	0.08	1	100%		0
	bio-PE (Polyethylene) not biodegradable	0.00E+00	0.40	1	10%		0
	Copper (Primary)	1.22E-09	0.80	1	10%		9.77E-10
	Aluminum (Primary)	9.95E-10	0.80	1	10%		7.961E-10

Transport		Eco-intensity (impacts/ ton-km)	Mass per item (ton)	Distance per item (km)	Items per func.unit (#)	Uncertainty %	Notes	Calculated Impact
	Ocean Freight	0.00E+00	0.008	8800	1	10%		0
	Truck+Container	1.15E-11	0.008	4700	1	30%		4.33E-10

Use		Eco-intensity (impacts/MJ or other)	Amount per item (MJ or other)	Items per func.unit (#)	Uncertainty %	Notes	Calculated Impact
	Electricity Sri Lanka Production	0.000000	365	10	10%		0
	Electricity Sri Lanka Production						0

End of Life		Eco-intensity (impacts/kg)	Mass per item (kg)	Items per func.unit (#)	Uncertainty %	Notes	Calculated Impact
	LiFePO4 Lithium Iron Phosphate	0.000000	3.2	1	10%		0
	Graphite for Batteries	0.000000	2	1	10%		0
	Ethylene Carbonate Organic Solvent	0.000000	0.72	1	10%		0
	LiPF6 Lithium Hexafluorophosphate	0.000000	0.08	1	10%		0
	bio-PE (Polyethylene) not biodegradable	0.000000	0.4	1	10%		0
	Copper (Primary)	0.000000	0.8	1	10%		0
	Aluminum (Primary)	0.000000	0.8	1	10%		0

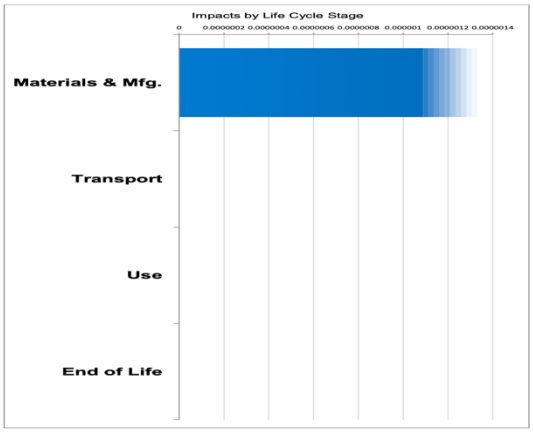


Fig. 8 Ozone depletion impacts of each phase – Option A

A comparison of the total ozone depletion impacts of Option A, which uses copper and aluminum as primary materials, vs. Option B, which has copper and aluminum as recycled materials, is performed using the Environmental Footprint 3.1 Ozone Depletion method. The results indicate that Option A achieves the environmental intent, but Option B is slightly less effective.

Lower total impact. In Option B, the lower energy requirements and emissions associated with producing recycled copper and aluminum, relative to their primary counterparts, significantly reduce ozone-depleting impacts.

Primary metals are produced through energy-intensive extraction and refining processes that contribute to ozone depletion by releasing pollutants. On the other hand, recycling processes bypass the need to extract raw materials, require less energy, and produce fewer emissions of ozone-depleting substances. The impacts of the two options differ slightly, but the reduction of impacts in Option B shows that recycling is important with secondary materials

usage to improve sustainability. Recycling materials reduces the need for virgin materials and avoids particulate emissions, thereby helping to prevent the depletion of the ozone layer. This comparison confirms the utility of reducing environmental impacts in categories such as ozone depletion, where greenhouse gas emissions are relatively low, by adopting recycling practices.

Manufacturing		Eco-intensity (impacts/kg)	Mass per item (kg)	Items per func.unit (#)	Uncertainty %	Notes	Calculated Impact
	LiFePO4 Lithium Iron Phosphate	3.74E-07	3.20	1	10%		1.198E-06
	Graphite for Batteries	5.32E-09	2.00	1	10%		1.065E-08
	Ethylene Carbonate Organic Solvent	0.00E+00	0.72	1	30%		0
	LiPF6 Lithium Hexaflourophosphate	0.00E+00	0.08	1	100%		0
	bio-PE (Polyethylene) not biodegradable	0.00E+00	0.40	1	10%		0
	Copper (Primary)	1.22E-09	0.80	1	10%		9.77E-10
	Aluminum (Primary)	9.95E-10	0.80	1	10%		7.961E-10
							0
							0
							0
							0
							0
							0
							0
							0
							0

Transport		Eco-Intensity (impacts/ ton-km)	Mass per item (ton)	Distance per item (km)	Items per func.unit (#)	Uncertainty %	Notes	Calculated Impact
	Ocean Freight	0.00E+00	0.008	8800	1	10%		0
	Truck+Container	1.15E-11	0.008	4700	1	30%		4.33E-10
								0
								0

Use		Eco-Intensity (impacts/MJ or other)	Amount per item (MJ or other)	Items per func.unit (#)	Uncertainty %	Notes	Calculated Impact
	Electricity Sri Lanka Production	0.000000	365	10	10%		0
	Electricity Sri Lanka Production						0

End of Life		Eco-Intensity (impacts/kg)	Mass per item (kg)	Items per func.unit (#)	Uncertainty %	Notes	Calculated Impact
	LiFePO4 Lithium Iron Phosphate	0.000000	3.2	1	10%		0
	Graphite for Batteries	0.000000	2	1	10%		0
	Ethylene Carbonate Organic Solvent	0.000000	0.72	1	10%		0
	LiPF6 Lithium Hexaflourophosphate	0.000000	0.08	1	10%		0
	bio-PE (Polyethylene) not biodegradable	0.000000	0.4	1	10%		0
	Copper (Primary)	0.000000	0.8	1	10%		0
	Aluminum (Primary)	0.000000	0.8	1	10%		0
							0

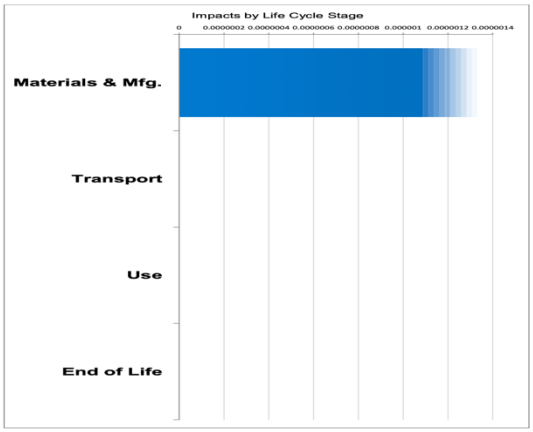


Fig. 8 Ozone depletion impacts of each phase – Option A

Manufacturing		Eco-intensity (impacts/kg)	Mass per item (kg)	Items per func.unit (#)	Uncertainty %	Notes	Calculated Impact
	LiFePO4 Lithium Iron Phosphate	3.74E-07	3.2	1	10%		1.198E-06
	Graphite for Batteries	5.32E-09	2	1	10%		1.065E-08
	Ethylene Carbonate Organic Solvent	0.00E+00	0.72	1	30%		0
	LiPF6 Lithium Hexaflourophosphate	0.00E+00	0.08	1	100%		0
	bio-PE (Polyethylene) not biodegradable	0.00E+00	0.4	1	10%		0
	Copper (Secondary)	1.40E-11	0.8	1	10%		1.124E-11
	Aluminum (Secondary)	8.98E-10	0.8	1	10%		7.186E-10

Transport		Eco-Intensity (impacts/ ton-km)	Mass per item (ton)	Distance per item (km)	Items per func.unit (#)	Uncertainty %	Notes	Calculated Impact
	Ocean Freight	0.00E+00	0.008	8800	1	10%		0
	Truck+Container	1.15E-11	0.008	4700	1	30%		4.33E-10

Use		Eco-Intensity	Amount per item	Items per func.unit (#)	Uncertainty %	Notes	Calculated Impact
	Electricity Sri Lanka Production	0.000000	365	10	10%		0
							0
							0

End of Life		Eco-Intensity (impacts/kg)	Mass per item (kg)	Items per func.unit (#)	Uncertainty %	Notes	Calculated Impact
	LiFePO4 Lithium Iron Phosphate	0.000000	3.2	1	10%		0
	Graphite for Batteries	0.000000	2	1	10%		0
	Ethylene Carbonate Organic Solvent	0.000000	0.72	1	10%		0
	LiPF6 Lithium Hexaflourophosphate	0.000000	0.08	1	10%		0
	bio-PE (Polyethylene) not biodegradable	0.000000	0.4	1	10%		0
	Copper (Secondary)	0.000000	0.8	1	10%		0
	Aluminum (Secondary)	0.000000	0.8	1	10%		0

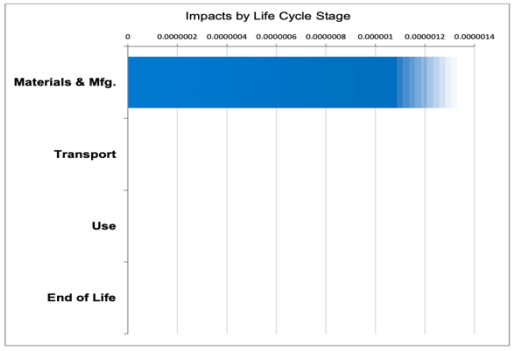
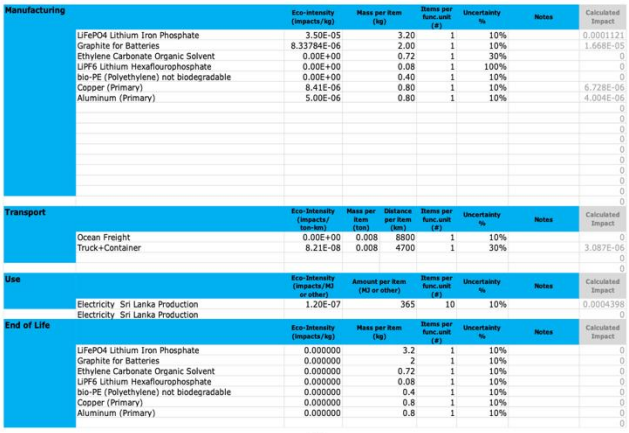


Fig. 9 Ozone depletion impacts of each phase -Option B

4.1.5 EF3.1 Marine Eutrophication (Marine Eutrophication)

Environmental Footprint 3.1 Marine Eutrophication method is used to compare the total marine eutrophication impacts between options A and B. Primary copper and aluminum are used in option A. Recycled copper and aluminum are used in option B. Results demonstrate that Option B has a slightly lesser total effect than Option A, implying the environmental benefits of tapping into recycled materials in battery products. Minimized nutrient emissions during the production of recycled metals play a key role in reducing the impact of marine eutrophication under Option B. Various mining, refining, and smelting processes associated with primary metal production generate significant releases of metals and other pollutants, which are ultimately discharged into water bodies and contribute to nutrient loading and eutrophication. Recycling reduces energy requirements (lower emissions and less nutrient runoff) and avoids the time and energy required to extract raw materials. Although the two options are slightly different, the lower impacts demonstrated for Option B highlight the benefits of the use of recycled materials to minimize the environmental costs. Resource efficiency is improved by promoting recycling and using recycled copper and aluminum in manufacturing, while reducing nutrient emissions. It is consistent with sustainability objectives while helping to reduce the total marine eutrophication potential associated with lithium-ion batteries.



Manufacturing		Eco-intensity (impacts/kg)	Mass per item (kg)	Items per func.unit (#)	Uncertainty %	Notes	Calculated Impact
	LiFePO4 Lithium Iron Phosphate	3.50E-05	3.20	1	10%		0.0001121
	Graphite for Batteries	8.33784E-06	2.00	1	10%		1.668E-05
	Ethylene Carbonate Organic Solvent	0.00E+00	0.72	1	30%		0
	LiPF6 Lithium Hexafluorophosphate	0.00E+00	0.08	1	100%		0
	bio-PE (Polyethylene) not biodegradable	0.00E+00	0.40	1	10%		0
	Copper (Primary)	8.41E-06	0.80	1	10%		6.728E-06
	Aluminum (Primary)	5.00E-06	0.80	1	10%		4.004E-06
							0
							0
							0
							0
							0
							0
							0
							0
							0
							0

Transport		Eco-intensity (impacts/ ton-km)	Mass per item (ton)	Distance per item (km)	Items per func.unit (#)	Uncertainty %	Notes	Calculated Impact
	Ocean Freight	0.00E+00	0.008	8800	1	10%		0
	Truck+Container	8.21E-08	0.008	4700	1	30%		3.087E-06
								0
								0

Use		Eco-intensity (impacts/MJ or other)	Amount per item (MJ or other)	Items per func.unit (#)	Uncertainty %	Notes	Calculated Impact
	Electricity Sri Lanka Production	1.20E-07	365	10	10%		0.0004398
	Electricity Sri Lanka Production						0

End of Life		Eco-intensity (impacts/kg)	Mass per item (kg)	Items per func.unit (#)	Uncertainty %	Notes	Calculated Impact
	LiFePO4 Lithium Iron Phosphate	0.000000	3.2	1	10%		0
	Graphite for Batteries	0.000000	2	1	10%		0
	Ethylene Carbonate Organic Solvent	0.000000	0.72	1	10%		0
	LiPF6 Lithium Hexafluorophosphate	0.000000	0.08	1	10%		0
	bio-PE (Polyethylene) not biodegradable	0.000000	0.4	1	10%		0
	Copper (Primary)	0.000000	0.8	1	10%		0
	Aluminum (Primary)	0.000000	0.8	1	10%		0
							0

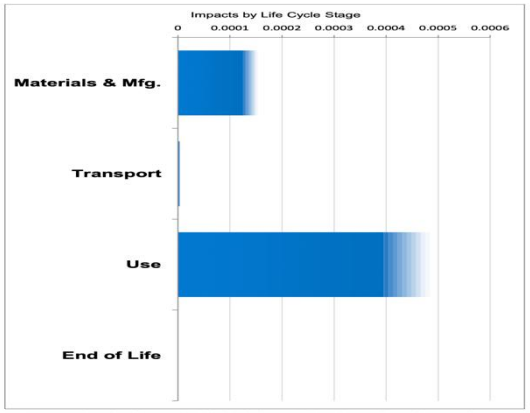


Fig. 9 Marine Eutrophication impacts of each phase -Option A

Manufacturing		Eco-intensity (impacts/kg)	Mass per item (kg)	Items per func.unit (#)	Uncertainty %	Notes	Calculated Impact
	LiFePO4 Lithium Iron Phosphate	3.50E-05	3.2	1	10%		0.0001121
	Graphite for Batteries	8.33784E-06	2	1	10%		1.668E-05
	Ethylene Carbonate Organic Solvent	0.00E+00	0.72	1	30%		0
	LiPF6 Lithium Hexafluorophosphate	0.00E+00	0.08	1	100%		0
	bio-PE (Polyethylene) not biodegradable	0.00E+00	0.4	1	10%		0
	Copper (Secondary)	3.65E-07	0.8	1	10%		2.917E-07
	Aluminum (Secondary)	4.13E-07	0.8	1	10%		3.305E-07

Transport		Eco-intensity (impacts/ ton-km)	Mass per item (ton)	Distance per item (km)	Items per func.unit (#)	Uncertainty %	Notes	Calculated Impact
	Ocean Freight	0.00E+00	0.008	8800	1	10%		0
	Truck+Container	8.21E-08	0.008	4700	1	30%		3.087E-06

Use		Eco-intensity	Amount per item	Items per func.unit (#)	Uncertainty %	Notes	Calculated Impact
	Electricity Sri Lanka Production	1.20E-07	365	10	10%		0.0004398
							0
							0

End of Life		Eco-intensity (impacts/kg)	Mass per item (kg)	Items per func.unit (#)	Uncertainty %	Notes	Calculated Impact
	LiFePO4 Lithium Iron Phosphate	0.000000	3.2	1	10%		0
	Graphite for Batteries	0.000000	2	1	10%		0
	Ethylene Carbonate Organic Solvent	0.000000	0.72	1	10%		0
	LiPF6 Lithium Hexafluorophosphate	0.000000	0.08	1	10%		0
	bio-PE (Polyethylene) not biodegradable	0.000000	0.4	1	10%		0
	Copper (Secondary)	0.000000	0.8	1	10%		0
	Aluminum (Secondary)	0.000000	0.8	1	10%		0

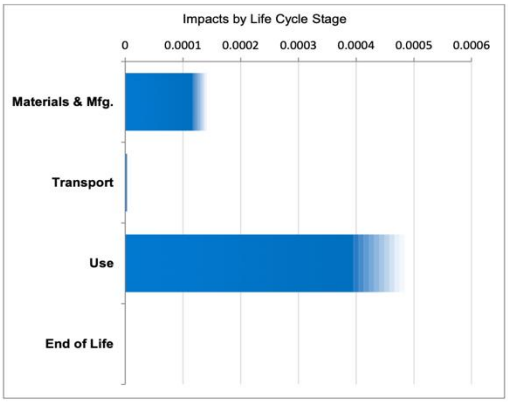


Fig. 11 Marine Eutrophication impacts of each phase -Option B

5. Conclusion

This research investigates the application of household lithium-ion batteries ($LiFePO_4$ chemistry) on solar energy storage systems in Sri Lanka and comprehensively evaluates their environmental impacts. Life cycle assessment (LCA) methodologies were used to analyze the data from surveys, literature, industry input, and the IDEMAT 2024 Excel database. Several environmental impact categories, including global warming potential (GWP), resource depletion, acidification, marine eutrophication, and others, were assessed across a range of key lifecycle stages: materials and manufacturing; transport; use; and end of life, using established LCIA methods, including ReCiPe 2016 and Environmental Footprint 3.1. What the results show is that in most categories, including the two most indicative, global warming potential and acidification, electricity consumption in the use phase completely overwhelms its other impacts during a battery's 10-year lifespan. From this, it is evident that the energy source plays the most important role in shaping the whole environmental performance of lithium-ion batteries. This also has the potential to substantially reduce these impacts by transitioning to a renewable energy source for battery charging — rather than grid electricity, which may (or may not) be largely fossil fuel-dependent. The second-largest contributor to environmental burdens was identified as the materials and manufacturing stage, driven by the extraction, refining, and processing of raw materials such as lithium, aluminum, and copper. These processes are resource-intensive and linked to emissions that contribute to climate change, acidification, and toxic impacts. In contrast, the environmental impacts of the transport and end-of-life stages were comparatively minimal. However, recycling rates and sustainable disposal can be improved, and these additional measures can positively affect environmental performance. Comparing Option A (primary copper and aluminum) with Option B (recycled copper and aluminum) highlights the environmental benefits of recycled materials in battery production. Recycling consistently ranks highest across all evaluated categories, including resource depletion, ozone depletion, and acidification, underscoring its importance in reducing demand for virgin material extraction and associated emissions. These results are consistent with global sustainability goals and suggest integrating circular economy principles into battery manufacturing and lifecycle management. In addition, this study also highlights the real need for newly developed recycling infrastructure and awareness in Sri Lanka. Inadequate information, along with limited facilities, was identified in the survey data as a major barrier to proper battery recycling. Several policy interventions, public education, and investments in recycling infrastructure can help mitigate the environmental impacts of end-of-life battery disposal. Finally, this work offers important lessons about the lifecycle impacts of lithium-ion batteries used in solar storage systems. The findings highlight that future energy charging should rely on renewable energy sources and that efficiency and recycling should play an important role in mitigating environmental impact. Additionally, improving recycling practices and adopting a circular economy approach will significantly further the sustainability of lithium-ion batteries in Sri Lanka. Not only do these recommendations help reduce the environmental impact of batteries, but they also align with the country's broader aspirations to pursue sustainable energy transitions.

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Integrating Corporate Communication Skills into English Language Teaching: Empowering Prospective English Teachers at Sri Lankan Colleges of Education for 21st- Century Employability

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Abstract: This study examines how corporate communication skills can be integrated into English Language Teaching (ELT) at Sri Lankan Colleges of Education to enhance the employability of prospective English teachers in the 21st century. As future educators, these trainees play dual roles: teaching language and fostering professional skills that extend beyond the classroom. However, traditional ELT in Sri Lanka has largely focused on grammar and literature, paying limited attention to workplace communication needs, including professional writing, presentations, negotiations, intercultural awareness, digital communication, and teamwork. To address this gap, the research proposes embedding corporate communication competencies into teacher training programs. A mixed-methods approach will be used to collect quantitative data from prospective teachers through surveys and qualitative data from teacher educators through interviews, focus groups, and classroom observations. The study will analyze current teaching practices, identify gaps in teacher preparation for the demands of the modern workplace, and explore the potential benefits of integrating these skills into ELT training. The anticipated findings suggest that equipping trainee teachers with corporate communication skills will not only improve their own employability but also enable them to nurture future-ready communication abilities in their students. Ultimately, the research advocates a transformative shift in English teacher education to align with global workforce trends and national development.

Keywords: Corporate Communication Skills, English Language Teaching (ELT), Teacher Education, Employability, Prospective English Teachers

1 Introduction

1.1 Background of the study

English has a major role in Sri Lanka as a connecting language and a gateway to both domestic and foreign employment and higher education. There is a greater need for competent English teachers who possess both professional and practical communication abilities. However, rather than emphasizing workplace-oriented communication skills essential to the job environment, Sri Lankan teacher education programs primarily focus on linguistic precision, grammar, and literature. As a result, there is now a disconnect between the training offered to aspiring English teachers at colleges of education and the communication needs of the contemporary world.

Through academic training and practical applications, corporate communication skills are integrated into English Language Teaching (ELT). It shifts from teaching English as a stand-alone subject to recognizing it as a life skill essential for workplace success. Since aspiring English teachers will eventually become facilitators who influence the employability and communication skills of future generations, they must strengthen these skills during their pre-service training. Therefore, the purpose of this study is to investigate how corporate communication skills can be successfully incorporated into English language instruction at Sri Lankan Colleges of Education and how this integration can enable aspiring English teachers to meet the demands of both pedagogy and employability in the twenty-first century.

Additionally, teaching employment skills to graduates may be deemed a national requirement. Soft skills, including critical thinking, creativity, communication for sustainable development, and universal keenness, were emphasized in Sri Lanka's National Education Policy Framework (2020) and educational reforms (2025). Prospective educators have implemented these policies to prepare the next generation of global citizens for the workforce. Communication skills can become a socioeconomic advantage. Teacher candidates should strengthen their global citizenship skills to build professional confidence.

1.2 Context of Sri Lanka's English Teacher Education System

Sri Lanka's teacher education system comprises a network of National Colleges of Education (NCOEs), which prepare aspiring teachers for primary and secondary education. One of the most popular specializations among these is English as a Second Language (ESL), reflecting the nation's growing need for English proficiency. The NCOE curriculum, which usually lasts three years, combines language enhancement courses, theoretical training, and hands-on teaching experience. This underscores the importance of incorporating workplace communication skills into teacher education programs in a methodical, pedagogically sound way.

1.3 Research Problem, Objectives, and Significance

The central problem addressed by this study is the **absence or insufficient integration of corporate communication skills in the English teacher education curricula** at Sri Lankan Colleges of Education. This gap limits the employability and professional readiness of prospective English teachers and, by extension, constrains their capacity to nurture workplace-oriented communication skills among school students.

The **objectives** of the study are as follows:

1. To investigate the current status of corporate communication skill integration within English teacher training curricula in Sri Lankan Colleges of Education.
2. To identify the perceptions of teacher trainees and teacher educators regarding the relevance and importance of corporate communication skills in English language teaching.
3. To explore practical strategies for embedding corporate communication skills into the existing ELT framework at the pre-service teacher education level.
4. To assess the potential impact of such integration on the employability and professional development of prospective English teachers.

Ultimately, this project aims to close the current gap between academia and the workplace by supporting a cutting-edge teacher education model that equips Sri Lankan English instructors to succeed in fast-paced, internationally connected settings. Future educators can be equipped to guide their students toward linguistic proficiency, professional self-assurance, and long-term success by integrating business communication skills into English language instruction.

2 Literature Review

2.1 Conceptualizing Corporate Communication Skills

Corporate communication is the organized set of techniques businesses use to maintain connections with internal and external stakeholders. It has historically encompassed professional presentations, report writing, public relations, and business correspondence. Digital communication, intercultural communication, negotiation, conflict resolution, and teamwork in organizational contexts have all been added to the scope of business communication in recent decades (Cornelissen, 2020). These skills are essential in today's business environment, where success is determined by teamwork, leadership, and intercultural communication. Corporate communication skills enhance the educational framework of English Language Teaching (ELT) by converting English from a strictly academic subject into a practical, skill-based discipline. A. Corporate communication emphasizes purpose, audience, clarity, and context more than traditional English training, which often focuses on grammatical accuracy and literary interpretation. According to Ellis (2019), language instruction that incorporates practical communication techniques improves students' pragmatic competence. Learning corporate communication skills for teacher candidates includes knowing how to teach these competencies to future students and how to communicate effectively in professional contexts. Therefore, integrating these abilities into teacher education programs produces teachers who are both linguistically competent and professionally adaptable, bridging the gap between classroom instruction and workplace communication.

2.2 Theoretical Foundations: From Communicative Competence to Employability

Several well-known theoretical stances provide the foundation for incorporating business communication into ELT. The most important of these is Hymes' (1972) Communicative Competence Theory, which expands the notion of language competence to encompass sociolinguistic, discourse, and strategic competence in addition to grammatical accuracy.

Subsequent models, such as Canale and Swain's (1980) framework, highlighted that proficient language use across a variety of social contexts is just as important to effective communication as understanding linguistic principles. Since corporate communication takes place in intentional, context-sensitive, and often high-stakes settings, it closely adheres to these principles. Building on communicative competence, the **21st Century Skills Framework** developed by the Partnership for 21st Century Learning (P21, 2019) identifies communication, collaboration, critical thinking, and creativity as core competencies for global citizenship and employability. Within this framework, English language education is viewed as a vehicle for developing transferable communication skills applicable to professional life. Similarly, the **Employability Skills Framework** (Australian Department of Education, 2018) underscores communication as one of the eight essential competencies that enable individuals to gain and maintain employment. According to these theories, communication should be taught in teacher education as a complex ability integrated into social interaction and workplace functioning, rather than as an isolated linguistic phenomenon. When prospective English teachers acquire these skills, they will be able to design classroom environments that reflect real-world communicative situations, which aligns with the approaches of Task-Based Language Teaching (TBLT) and Communicative Language Teaching (CLT).

2.3 Previous Research and Identified Gaps

The relationship between language instruction and employability in Sri Lankan and international contexts has been studied by several academics. According to Wickramasinghe and Perera (2020), Sri Lankan undergraduates enrolled in English-medium programs frequently struggle with formal communication and report-writing assignments, underscoring the need for specialized professional English training. In a similar vein, Rajapaksha (2019) observed that many English teachers are not familiar with contemporary business communication tools, including online presentation platforms, LinkedIn networking, and email etiquette, resulting in limited incorporation of these tools in classroom instruction.

Studies worldwide by Kaur (2022) and Lee (2021) found that pre-service teachers with corporate communication training have higher self-efficacy in handling classroom communication and fostering students' soft skills. This research highlights the importance of including professional communication courses in teacher education. However, there remains a dearth of empirical research on this integration in Sri Lanka. There is little research on English for Professional or Corporate Communication in pre-service teacher education; instead, most accessible studies focus on general communicative ability or English for Academic Purposes (EAP).

Thus, by methodically examining how corporate communication skills might be incorporated into English teacher preparation at the NCOE level, the current study aims to close this gap. In addition to identifying current shortcomings, it offers a paradigm for integrating professional communication techniques into ELT instruction.

3 Methodology

3.1 Research Design

To obtain a thorough understanding of how corporate communication skills can be incorporated into English language instruction at Sri Lankan Colleges of Education, this study employs a mixed-methods research design integrating quantitative and qualitative approaches. The complexity of the study problem, which includes contextual and experiential insights that cannot be captured by quantitative data alone, as well as measurable perceptions and competencies, justifies the use of mixed methodologies.

The **quantitative component** of the study aims to identify patterns, trends, and general perceptions among prospective English teachers regarding the relevance and practice of corporate communication skills in their training programs. Meanwhile, the **qualitative component** focuses on an in-depth exploration of teacher educators' and trainees' experiences, attitudes, and recommendations regarding the integration of these skills into English teacher education. By triangulating both forms of data, the study ensures greater validity, reliability, and contextual richness in its conclusions.

3.2 Population and Sample

Prospective English teachers and teacher educators affiliated with specific National Colleges of Education (NCOEs) in Sri Lanka that offer English as a major specialization constitute the study's target demographic. There are currently about 19 NCOEs nationwide, including reputable institutions such as Pasdunrata, Polgolla, and Peradeniya Colleges of Education. Three ELT offers NCOEs.

We will use a multi-stage sampling approach. To ensure diversity across institutional contexts, three NCOEs will be purposively selected in the initial round to represent various geographic regions (Western and Central). In the second round, 150 aspiring English teachers -roughly 50 from each college -will be chosen at random to take part in the quantitative survey.

Purposive sampling will be used to select 15 teacher educators (five from each chosen college) for the qualitative component, based on their backgrounds in curriculum design, English language instruction, or teacher preparation. To foster shared experiences and collective views, three focus group discussions (FGDs) with groups of eight to ten teacher candidates will be held. This mix of participants ensures that the data reflects viewpoints from instructors and students across the teacher education ecosystem.

3.3 Research Instruments

Several tools will be used to gather both quantitative and qualitative data:

1. Questionnaire for Future Teachers:

To collect information on trainees' awareness, perceptions, and self-assessed competencies across a range of corporate communication skills, including professional writing, presentations, teamwork, negotiation, and digital communication, a structured questionnaire will be developed. Both open-ended questions and Likert-scale items will be included in the survey to allow for qualitative elaboration and quantitative assessment of opinions. To ensure clarity and reliability, the instrument will be confirmed through expert evaluation and pilot testing.

2. Teacher Educators' Guide to Semi-Structured Interviews.

To learn more about teacher educators' opinions on the existing English language teaching curriculum, their understanding of corporate communication, and their thoughts on how these abilities might be incorporated into pre-service teacher training, an interview guide will be developed. Participants can exchange experiences and examples in depth thanks to the flexibility of the semi-structured format.

3. Focus Group Discussion (FGD) Protocol:

To promote candid discussion among teacher candidates about employability skills in their programs, FGDs will be held. With permission, each session will be audio-recorded for transcription and analysis and will last between 60 and 90 minutes.

4. Classroom Observation Checklist:

To determine whether components of workplace communication are present in current pedagogical methods, non-participant classroom observations will be conducted during designated language-teaching sessions. The checklist will include indicators such as digital communication tasks, cooperative exercises, communicative activities, and the use of real resources.

3.4 Data Collection Procedures

Over four months, the data collection will occur in three consecutive rounds.

Phase 1: Administration of Quantitative Surveys. To ensure a response rate above 90%, the researcher will personally deliver the surveys to aspiring English instructors during their academic sessions. Confidentiality will be guaranteed, and prior to participation, informed consent will be acquired.

Phase 2: Gathering Qualitative Information. Teacher educators at each college will participate in semi-structured interviews after the survey. With consent, each interview will be recorded for approximately 45-60 minutes. To promote candid conversation, the FGDs with trainees will take place after school hours.

Phase 3: Classroom Observations. A sample of 10 instructional sessions from each college will be observed. The field notes will cover, in depth, the use of communicative techniques and teaching strategies, with references to professional or business communication contexts.

3.5 Data Analysis

SPSS will be used to analyze quantitative data from the questionnaires, using both descriptive and inferential statistics. Inferential tests (t-tests) may be used to investigate correlations between demographic characteristics and opinions on corporate communication abilities. At the same time, descriptive statistics (means, frequencies, and percentages) will

summarize participants' awareness and attitudes. Following Braun and Clarke's (2006) six-step framework - familiarization, coding, theme generation, review, definition, and interpretation -qualitative data from interviews, focus group discussions, and observations will be subjected to thematic analysis. Thematic analysis will enable the identification of recurring themes, insights, and challenges in integrating corporate communication into teacher education.

3.6 Ethical Considerations

The entire study procedure will be conducted with ethical integrity. Prior to data collection, permission will be obtained from the appropriate academic and institutional authorities. The goal, methods, and voluntary nature of the study will be explained to participants. Every participant will provide written informed consent. Pseudonyms and data coding to prevent personal identification will protect confidentiality. Participants will not be penalized for deciding to leave the study at any point. Data will be kept safe and used only for educational purposes.

3.7 Limitations of the Methodology

The study may have some limitations, even though the mixed-methods methodology offers thorough insights. Although representative, the sample size might not adequately capture differences across all NCOEs. Additionally, self-reported survey data may reflect perceived rather than actual communication proficiency. Time constraints may also limit long-term classroom observation. Nevertheless, scientific triangulation, cross-validation, and cautious data interpretation help lessen these restrictions.

4 Findings and Discussion

4.1 Overview

The outcomes of the mixed-methods data collection, comprising quantitative survey data from 150 aspiring English teachers and qualitative information from focus groups, interviews, and classroom observations, are presented and interpreted in this part. Together, the data show how corporate communication skills are currently integrated into English teacher education at Sri Lankan Colleges of Education (NCOEs), how trainees and educators view their significance, and the potential advantages and challenges of incorporating these skills into English Language Teaching (ELT). According to the goals of the study, the analysis is divided into four major themes:

1. Current procedures and exposure to corporate communication techniques.
2. Views of significance and relevance.
3. Determined curricular gaps and obstacles.
4. Possible approaches and integration effects.

4.2 Current Practices and Exposure to Corporate Communication Skills

According to the quantitative data, more than 70% of respondents agreed that teaching methodology, literary analysis, and grammatical precision were more important in their English education courses than professional communication. Just 18% of respondents reported receiving formal training in corporate communication subjects, including professional presentation, public speaking, and business writing. Additionally, fewer than 15% of trainees reported familiarity with job-related communication genres, such as negotiating language, report writing, and email etiquette. Classroom observations corroborated these results. The majority of the lessons were conventional, emphasizing vocabulary, structure, and literary understanding with little use of real-world materials or simulation exercises. Educators and trainees rarely use role-plays, discussions, and case studies that simulate workplace communication scenarios. These findings are consistent with earlier research (Perera, 2021; Rajapaksha, 2019) showing that academic English is given more importance in Sri Lankan teacher education programs than professional and functional communication. Prospective teachers may enter the industry with little confidence in managing communication outside the classroom, due to limited exposure to corporate communication practices during pre-service training. In contrast, English for Employability modules are incorporated into teacher education curricula in countries such as Malaysia and Singapore (Nair & Ng, 2021). Sri Lanka's lack of comparable integration highlights the need for curriculum modernization to align with English education and workplace realities.

4.3 Perceptions of Relevance and Importance

The majority of trainees demonstrated a strong awareness of the importance of corporate communication skills despite their limited exposure. Approximately 92% of poll participants felt that these abilities are necessary for success in the workplace, and 86% thought English teachers ought to be prepared to teach communication outside of the classroom. Additionally, 80% of trainees expressed a desire to acquire useful communication skills to improve their employability and teaching opportunities. Many trainees acknowledged communication as a critical component in obtaining and maintaining employment, according to focus group talks. "We study English for years, but when we face an interview or have to present in front of others, we realize how much we lack confidence in real communication."

These opinions were shared by teacher educators, who acknowledged that conventional curricula are outdated and fail to adequately prepare educators for contemporary work environments. In addition to teaching proficiency, companies now demand that English teachers have strong interpersonal, digital, and cross-cultural communication skills, according to several educators. These results are consistent with views on education- employment alignment around the world. UNESCO (2021) and the World Economic Forum (2023) both emphasize communication as a "future skill" necessary for employability in the twenty-first century. The study reaffirms that incorporating business communication components into English language instruction can effectively foster these skills.

4.3 Identified Gaps and Barriers

4.3.1 Curriculum Limitations

The current English teacher education curriculum lacks specific modules or organized content on professional communication, according to an analysis of institutional records and interviews. Although some CLT (Communicative Language Teaching) courses incorporate communicative exercises, these are more pedagogical than professional. According to teacher educators, new skill areas, such as digital or intercultural communication, have not yet been systematically incorporated into the curriculum, and curriculum updates are rare.

4.3.2 Limited Resource and Training Opportunities

The lack of adequate corporate or professional communication training among teacher educators was a recurring theme in the qualitative data. Several instructors acknowledged having limited exposure to corporate settings or organizational communication. As a result, they frequently felt unprepared to guide trainees in these domains. Another major obstacle was the absence of guest lecturers, workshops, or industry connections.

4.3.3 Assessment and Pedagogical Constraints

Observations in the classroom revealed that evaluation procedures remain largely exam-based, with a strong emphasis on written, grammar-based exams. "We encourage communicative teaching, but at the end of the day, the evaluation system rewards theoretical knowledge, not communicative performance," a teacher noted. This distance deters teachers and students from participating in practical communication exercises. Furthermore, opportunities for digital communication practice -a crucial aspect of modern corporate communication -are limited in certain NCOEs due to their inadequate technological infrastructure. Together, these obstacles explain why effective integration of communication skills into the curriculum has not yet been achieved.

4.4 Summary of Findings

The study concluded that:

- There is little exposure to corporate communication skills in Sri Lanka's current English teacher training programs.
- Both trainees and educators recognize the relevance and necessity of these skills for professional and pedagogical success
- Outdated curricula, a lack of educator training, a lack of resources, and assessment practices that undervalue communication performance are major obstacles
- Incorporating corporate communication through curriculum reform, experiential learning, digital literacy, and industry collaboration can greatly improve student learning outcomes and teacher employability. The argument for a paradigm change in English teacher education -from conventional, knowledge-based instruction to a comprehensive, skill-oriented model that prepares teachers for the educational and professional

challenges of the twenty-first century is supported by these findings taken together.

5 Conclusion and Recommendations

5.1 Conclusion

Given that communication is now essential to modern professional success and is no longer limited to academic expression, the study found that Sri Lanka's teacher education system urgently needs to adapt its English-language courses to meet the expectations of the global workplace.

The mixed-methods investigation's findings showed that although English language instruction in colleges of education maintains solid foundations in grammar, literature, and pedagogy, it often overlooks the professional and practical communication skills required in today's work environments. Although they lacked structured opportunities to practice these skills in their training programs, teacher candidates demonstrated a modest understanding of corporate communication practices, including digital communication, public speaking, email etiquette, and negotiation. In a similar vein, teacher educators recognized the need for these competences. However, they identified curricular rigidity, a dearth of training materials, and limited exposure to the industry as significant obstacles to implementation.

The findings also showed that incorporating corporate communication into English teacher education offers two advantages: first, it makes teacher candidates more employable and self-assured as they enter professional environments; second, it equips them with the tools they need to teach their future students to communicate effectively in the workplace. The study basically emphasizes that 21st-century English teachers need to exemplify the language's usefulness in everyday communication in addition to teaching it.

English language instruction in Sri Lanka's colleges of education can become a dynamic, skills-oriented field by combining pedagogy and business discourse. This reform will support national educational innovation, socioeconomic advancement, and teachers' professional development. As a result, the findings support a paradigm shift in which English is taught as a life and career skill rather than as a subject.

5.2 Educational Implications

This study has ramifications for Sri Lanka's educational system at multiple levels:

1. Curriculum Reformation: Corporate communication modules that emphasize practical, performance-based competencies like professional correspondence, presentation skills, teamwork, leadership communication, and intercultural interaction should be incorporated into the current English teacher training curricula.
2. Teacher Educator Capacity Building: English teacher educators should have access to ongoing professional development programs so they may stay current on business discourse, corporate communication trends, and digital communication tools. This project can be strengthened through collaborations with academic institutions, businesses, and international organizations.
3. Pedagogical Transformation: Interactive, hands-on learning should be promoted in place of lecture-based training. The gap between classroom theory and real-world application can be closed through exercises such as digital presentations, cooperative projects, simulated meetings, and mock interviews.
4. Assessment Innovation: In addition to language accuracy, assessment methods ought to gauge professional flexibility and communicative effectiveness. In simulated business jobs, rubrics might evaluate aspects like audience awareness, tone, clarity, and confidence.
5. Institutional and Policy Support: To test and expand corporate communication integration throughout all Colleges of Education, the Ministry of Education and the National Institute of Education should offer financial support, policy frameworks, and technical assistance.

5.3 Recommendations

The following particular suggestions are put out in light of the findings:

Make the "Corporate Communication Skills for Teachers" module a required part of all NCOEs' English education diploma programs.

Form alliances with NGOs and businesses in the private sector to offer internships, workshops, and guest lectures that

expose students to real-world communication settings.

To improve digital literacy and e-communication skills, implement a blended learning approach that combines in-person instruction with online resources.

Promote interdisciplinary cooperation between the management and English language departments to create workplace communication, jointly focused on resources and tests.

To assess the efficacy of integrated curricula and pinpoint optimal practices for national adoption, conduct continuing research and monitoring.

Concluding Remarks

In conclusion, incorporating corporate communication skills into English language teacher education is not just a pedagogical improvement but also a strategic requirement for national growth in an increasingly interconnected world. Future English teachers in Sri Lanka will foster global communication competency rather than impart knowledge of grammar and literature. Equipping them with corporate communication skills ensures they are not just employable professionals but also change agents who can develop learners who are confident, communicative, and prepared for the future. The Sri Lankan Colleges of Education may integrate teacher preparation with the nation's economic goals and international educational standards by rethinking English-language instruction through a corporate communication lens. This is a crucial step towards a fully 21st-century model of teacher education.

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Circular Procurement Framework for High-Rise Residential Buildings in Sri Lanka Aligned with Net-Zero Energy Goals

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Abstract. This study develops a contractor evaluation framework to support the integration of circular procurement (CP) strategies within Sri Lanka's high-rise residential building sector, advancing national net-zero energy (NZE) ambitions. Mixed-methods research, expert interviews, and Relative Importance Index (RII) analysis were employed to identify, weight, and prioritize criteria reflecting contractor readiness for circular construction. Six major evaluation categories emerged: Experience and Technical Capability, Sustainability and Circularity Practices, Certifications and Compliance, Financial and Operational Readiness, Workforce Skills and Capacity, and Innovation and Supply Chain Readiness. Normalized RII-based weightings were mathematically assigned to formulate the Circular Procurement-Ready Contractor Evaluation Framework (CPR-CEF), integrating a Contractor Circular Readiness Score (CCRS) for tiered classification. Findings highlight Sustainability and Circularity Practices (22%) and Experience and Technical Capability (20%) as the most influential dimensions, underscoring the dual importance of technical competence and sustainability engagement. The CPR-CEF enables objective contractor assessment and can function as a prequalification, tender evaluation, or post-award monitoring tool. The study contributes a practical, quantitative approach to operationalizing CP principles in developing contexts, bridging the gap between policy intent and implementation in NZE-aligned construction procurement.

Keywords: Circular procurement, contractor evaluation, net-zero energy; high-rise buildings in Sri Lanka.

1. Introduction

Construction represents a critical path of urban sustainability challenges, as building materials and operations contribute significantly to global energy-related emissions and resource consumption [1]. Within this context, high-rise residential buildings are particularly influential owing to their scale and the intensive service requirements associated with HVAC, lighting, and water systems, which collectively drive city-level energy demand and embodied carbon. Circular procurement (CP), defined as procurement practices that emphasize longevity, reuse, recyclability, and whole-of-life value, has been identified as a potential pathway to mitigating both operational and embodied impacts while simultaneously supporting net-zero energy (NZE) objectives [2], [3]. However, realizing CP outcomes depends heavily on procurement mechanisms capable of reliably identifying contractors with the requisite technical expertise, systems integration capabilities, and incentive structures necessary to deliver on circular ambitions in complex NZE projects.

In Sri Lanka, the rapid vertical expansion of urban environments has revealed a misalignment between sustainability objectives and procurement practices. Contractor selection processes continue to be predominantly cost-driven and transactional, with limited emphasis on lifecycle costing, circularity indicators, or performance-based accountability measures [4], [5]. This gap is particularly evident when client or designer intentions to integrate circular or NZE principles are undermined by contractors' limited capacity to implement such measures. Specifically, the execution of circular material strategies, deployment of digital lifecycle management tools, organization of on-site waste logistics, and integration of renewable energy systems remain uneven within the local construction market.

Against this backdrop, the present study addresses two guiding questions: (i) What criteria are essential for evaluating contractors' capacity to implement circular and sustainable construction practices? and (ii) How can these criteria be operationalized into a practical contractor identification and selection framework tailored for circular procurement in NZE-oriented high-rise projects?

This paper advances two primary contributions. Empirically, it identifies and prioritizes stakeholder-derived criteria for CP readiness through the application of the Relative Importance Index (RII). Practically, it develops a structured and context-sensitive contractor evaluation framework, incorporating a transparent, RII-weighted marking scheme to inform tender evaluation and prequalification processes. The proposed framework aligns global best practices in CP such as lifecycle costing and performance-based contracting with the specific challenges of the Sri Lankan construction

sector, which include limited uptake of certification schemes, financial constraints facing SMEs, and weak regulatory enforcement mechanisms [6], [7].

1 Methodology

This paper adopts a mixed-methods research design to capture both practitioner perspectives and the empirical prioritization of contractor evaluation criteria. By integrating qualitative and quantitative phases, the study moved beyond anecdotal observations and developed a grounded, context-sensitive framework for CP in Sri Lanka's high-rise NZE sector.

Research Design

The methodological pathway consisted of three sequential stages:

I. Qualitative exploration – semi-structured interviews with key stakeholders were used to identify criteria and themes for contractor evaluation.

II. Quantitative prioritization – the criteria identified were validated and ranked through a structured questionnaire survey using the RII.

III. Framework development – findings from both stages were synthesized into an evaluation framework and an RII-based scoring scheme for practical application.

Data Collection

Qualitative phase (Interviews)

a) Participants: Senior professionals from contracting firms, consultants, and policy institutions with direct exposure to sustainable or high-rise projects in Sri Lanka.

b) Sample: 6 participants, selected through purposive sampling to ensure diversity of perspectives (contractors, consultants, policymakers).

c) Instrument: Semi-structured interview guide focusing on perceived challenges in contractor readiness, criteria currently considered in prequalification/tendering, and views on circular procurement requirements.

d) Procedure: Interviews were conducted in person and online, each lasting 45–60 minutes.

Quantitative phase (Survey)

a) Instrument: A structured questionnaire derived from the interview findings. Respondents rated each contractor evaluation criterion on a five-point Likert scale (1 = not important, 5 = very important).

b) Participants: 50 construction professionals across contractor, consultant, and client organizations. A stratified random sampling method was adopted to ensure diverse representation of construction professionals across different organizational roles and project types.

c) Response rate: 40 usable responses (80%), considered sufficient for RII analysis.

Data Analysis

Thematic Analysis. Interview transcripts were coded and grouped into categories following Braun and Clarke's [8] six-phase approach. This generated six overarching themes: prior experience, technical competence, workforce capacity, institutional/project-level systems, certification and compliance, and systemic constraints.

Relative Importance Index (RII). Quantitative responses were analyzed using the RII formula:

$$RII = \frac{\sum w}{A \times N} \quad (1)$$

Where w is the weighting assigned to each criterion (1–5), A is the highest possible score (5), and N is the total number of respondents. The RII values range from 0 to 1, with higher scores indicating higher perceived importance. This allowed ranking of contractor evaluation criteria and informed the weighted marking scheme in the framework.

Integration of Findings

Qualitative insights provided depth on contextual barriers and enablers of CP readiness, while quantitative results highlighted industry priorities. The triangulation of these phases supported the development of a multi-dimensional framework that is both evidence-based and operationally relevant to Sri Lanka's procurement environment.

2 Results: Contractor Capacity Evaluation Criteria

Overview

The qualitative and quantitative phases together provided a comprehensive picture of how contractors in Sri Lanka are currently evaluated, and how they should be evaluated, for their ability to support CP and NZE outcomes in high-rise residential projects. While cost continues to dominate as the default contractor selection criterion in practice, stakeholders consistently emphasized that such an approach fails to capture the capacities actually needed for NZE delivery. Thematic analysis identified six major clusters of evaluation criteria, which were then validated and prioritized using RII analysis.

The following subsections present the findings in two layers: first, the qualitative insights from interviews, which provide rich narratives of practitioner perspectives; and second, the quantitative RII results, which numerically confirm and rank the relative importance of specific criteria within each theme.

Thematic Findings

Prior Experience and Proven Track Record. One of the most frequently mentioned themes was contractors' prior exposure to sustainable or NZE-related projects. Interviewees stressed that tangible experience serves as a proxy for competence,

a) Contractors who had delivered LEED-certified or GREENSL®-certified projects were perceived as more reliable in meeting sustainability benchmarks.

b) Evidence of successfully managing construction waste, implementing energy-efficient systems, or adopting green materials was seen as critical in demonstrating capacity.

However, respondents also noted the scarcity of local NZE case studies. Many contractors have not had the opportunity to work on projects explicitly framed as circular or NZE, which makes this criterion unevenly applicable. Some feared that an overemphasis on prior NZE-specific experience could exclude SMEs that have technical potential but lack demonstrable projects in their portfolio. This reflects a tension also noted in international literature: while experience provides credibility [3], [9], it risks reinforcing path-dependency and disadvantaging emerging firms [6].

Technical Competence and Specialized Knowledge. Technical expertise was repeatedly highlighted as the core enabling factor for CP implementation. Interviewees described a range of competencies that distinguish contractors capable of contributing to NZE outcomes,

a) Digital tools: familiarity with Building Information Modeling (BIM), energy modeling, and lifecycle cost analysis.

b) Resource efficiency methods: experience with modular prefabrication, on-site waste segregation, and advanced water/energy-saving technologies.

c) Renewable integration: technical knowledge for installing solar PV, heat pumps, or biogas systems.

One consultant remarked, "You can write circularity into a contract, but unless the contractor can interpret BIM data, optimize material use, or integrate renewable systems, it stays on paper." This perspective aligns with Mhatre et al. [10], who argue that digital and analytical capacity is a precondition for operationalizing CE principles in construction.

Workforce Training and Capacity Building. Beyond technical knowledge at the management level, the capacity of the on-site workforce emerged as a practical determinant of success. Respondents described recurring challenges:

a) Laborers often lacked familiarity with waste segregation or precision installation required for NZE systems.

b) Middle managers were not consistently trained in documenting sustainability performance or monitoring resource use.

Some contractors had invested in in-house training programs, but most relied on ad hoc learning. Stakeholders called for structured, continuous professional development (CPD) that could institutionalize circular practices across the workforce. This finding aligns with Wadugodapitiya et al. [5], who highlight skills shortages as a systemic constraint in the Sri Lankan construction sector. Without sustained workforce training, CP commitments risk being undermined during execution.

Institutional and Project-Level Criteria. Several respondents emphasized the need for stronger institutional mechanisms to embed circularity at contractor level. These include:

a) Sustainability-focused prequalification systems that vet contractors before tendering.

b) Performance-based audits tied to contract clauses, ensuring that sustainability outcomes are verifiable.

c) Inclusion of sustainability officers or dedicated teams within contractor organizations.

Interviewees stressed that current tendering practices rarely enforce such criteria, resulting in "paper commitments" rather than measurable actions.

Certification, Standards, and Compliance. Certifications such as ISO 14001 (environmental management), ISO 50001 (energy management), and local ratings like GREENSL® were seen as valuable signals of contractor commitment. However, their relevance was contested:

a) Larger firms typically pursued international certifications, while SMEs often could not justify the cost.

b) Certification alone was seen as insufficient without contextual adaptation and enforcement.

One policymaker noted, "We can't create a system where lack of ISO excludes SMEs, but at the same time, we can't ignore the assurance these standards provide." This tension reflects caution against over-reliance on certification as a sole proxy for sustainability readiness.

Systemic and Market Constraints. Finally, interviewees pointed to broader structural limitations affecting contractor readiness:

a) SMEs in particular operate with limited margins, making investment in training or certifications difficult.

b) Unless clients explicitly require circular practices, contractors default to cost minimization.

c) Without precedents, both clients and contractors hesitate to adopt unfamiliar practices.

These systemic issues show the need for procurement frameworks that not only evaluate contractors but also reshape market incentives.

Quantitative Prioritization of Contractor Evaluation Criteria

To complement the qualitative insights, a structured RII analysis was conducted. This provided a numerical ranking of evaluation criteria across six categories, offering a more objective perspective on how stakeholders in Sri Lanka prioritize contractor readiness for circular and sustainable construction. Table 1 summarizes the results.

Table 1. Ranking of contractor evaluation criteria by RII

Criteria Category	Evaluation Criteria	RII	Rank
Experience & Technical Capability (A)	A1 - Digital tools adoption for resource efficiency (e.g., BIM, IoT)	0.88	1
	A2 - Technical expertise in sustainable building techniques (e.g., modular construction, passive design)	0.82	2
	A3 - Experience in projects using circular economy principles	0.61	3
	A4 - R&D initiatives for sustainability innovation	0.57	4

	A5 - Experience in Net-Zero Energy (NZE) construction projects	0.56	5
Sustainability & Circularity Practices (B)	B1 - Water conservation measures (e.g., rainwater harvesting, greywater recycling)	0.84	1
	B2 - Use of locally sourced, low-carbon, and recycled materials	0.82	2
	B3 - Strategies for minimizing construction waste and promoting reuse/recycling	0.82	2
	B4 - Adoption of renewable energy solutions on-site	0.68	4
	B5 - Implementation of circular design approaches (e.g., design for disassembly)	0.65	5
Certifications & Compliance (C)	C1 - Compliance with government sustainability regulations and green codes	0.85	1
	C2 - Holding sustainability certifications (e.g., LEED, BREEAM, EDGE)	0.75	2
	C3 - Implementation of Environmental Management Systems (e.g., ISO 14001)	0.73	3
	C4 - Compliance with circular procurement policies and standards	0.58	4
Financial & Operational Readiness (D)	D1 - Financial stability to support long-term sustainable practices	0.83	1
	D2 - Willingness to invest in sustainable construction technologies	0.71	2
	D3 - Use of life-cycle costing for material and process selection	0.66	3
	D4 - Transparent sustainability reporting and performance metrics	0.64	4
Workforce Skills & Capacity (E)	E1 - Training programs for workers on circular and sustainable construction practices	0.77	1
	E2 - Availability of skilled labor trained in sustainable methods	0.71	2
	E3 - Cross-disciplinary collaboration for sustainability projects	0.70	3
Innovation & Supply Chain Readiness (F)	F1 - Prefabrication and modular construction adoption	0.75	1
	F2 - Use of innovative eco-friendly materials (e.g., bio-based, carbon-negative)	0.68	2

	F3 - Circular supply chain management (closed-loop material cycles)	0.65	3

High-Ranked Priorities. Across all categories, digital tool adoption (RII = 0.88) emerged as the highest-ranked criterion, reflecting strong recognition that BIM, IoT, and lifecycle analysis are indispensable for managing material efficiency, energy modeling, and performance monitoring. Similarly, compliance with government sustainability regulations (RII = 0.85) and water conservation measures (RII = 0.84) were identified as core requirements, echoing stakeholders' emphasis on technical competence and regulatory alignment as fundamental enablers of circular procurement. Financial stability (RII = 0.83) was also ranked highly, showing that even in discussions of sustainability, financial capacity remains a practical determinant of contractor readiness. In terms of technical know-how, expertise in sustainable construction methods (RII = 0.82) such as modular design and passive cooling was rated among the top five criteria overall. Together, these findings suggest that immediate priorities revolve around digital competence, regulatory compliance, water efficiency, financial health, and applied technical expertise.

Moderate Priorities. Criteria such as sustainability certifications (RII = 0.75), prefabrication and modular construction (RII = 0.75), and training programs for workers (RII = 0.77) received moderately high scores, reflecting their recognized importance but also their uneven application in Sri Lanka. Respondents valued certifications as assurance mechanisms but warned against over-reliance, particularly in contexts where SMEs lack the resources to pursue them. Workforce training similarly ranked high in principle, though interview data revealed it remains sporadic and largely ad hoc. These mid-ranked priorities therefore highlight transitional areas, practices acknowledged as important but not yet fully embedded in the local construction ecosystem.

Low-Ranked Criteria. At the lower end, experience in NZE projects (RII = 0.56) and compliance with circular procurement policies (RII = 0.58) were given the least importance. This reflects the primary stage of NZE construction and the absence of established CP policy frameworks in Sri Lanka. Similarly, R&D initiatives (RII = 0.57) scored low, indicating that while innovation is valued in words, it is not yet perceived as a practical contractor requirement. Notably, circular supply chain management (RII = 0.65) and circular design approaches (RII = 0.65) also ranked low, suggesting that life-cycle-based circularity practices are still emerging concepts rather than mainstream criteria in contractor selection.

The RII results support the qualitative themes while offering sharper distinctions between core enablers and emerging aspirations. Three key insights emerge,

I. **Practical readiness outweighs aspirational goals.** Stakeholders place highest value on criteria that are already feasible in practice: digital tools, regulatory compliance, water conservation, and financial stability, while more forward-looking aspects (NZE-specific experience, circular supply chains) receive lower emphasis.

II. **Financial and technical capacities are intertwined.** High scores for both financial stability (0.83) and technical expertise (0.82) indicate that contractors must be capable not only of deploying advanced methods but also of sustaining these practices financially.

III. **Phased adoption is necessary.** The gap between high-ranked (digital tools, compliance, financial health) and low-ranked (NZE, CP-specific policies) criteria suggests that Sri Lanka's construction industry is at a transitional stage. Procurement systems will need to prioritize readily implementable criteria first, while gradually introducing more advanced circularity requirements.

Synthesis

The combined qualitative and quantitative analysis offers a solid understanding of contractor readiness for supporting circular procurement in high-rise NZE construction projects in Sri Lanka. By triangulating thematic insights with RII rankings, several consistencies and tensions emerge that are crucial for designing an actionable evaluation framework.

Convergence between Qualitative and Quantitative Insights. Both strands of data strongly emphasize the centrality of technical and institutional competence. Interview participants frequently stressed the importance of digitalization, advanced construction methods, and regulatory adherence. At the same time, the RII results confirmed this by placing digital tool adoption (RII = 0.88), regulatory compliance (RII = 0.85), and technical expertise in sustainable construction techniques (RII = 0.82) among the top-ranked priorities.

Similarly, the qualitative concerns about financial viability and market competitiveness were validated quantitatively, with financial stability (RII = 0.83) ranking within the top five criteria. This alignment highlights that the industry views financial and technical readiness not as separate domains, but as mutually reinforcing capabilities necessary for delivering NZE buildings.

Another point of convergence lies in resource efficiency and water management. Interviews identified water-saving measures and waste minimization as non-negotiable for sustainable procurement. The survey results corroborated this, with water conservation (RII = 0.84) and waste reduction strategies (RII = 0.82) ranked highly. Together, these findings establish resource stewardship as a universally recognized dimension of contractor evaluation.

Divergences and Gaps. Despite these overlaps, notable divergences highlight gaps in industry maturity. Qualitatively, stakeholders often expressed aspirational support for circularity through design-for-disassembly, closed-loop supply chains, and renewable energy integration. However, these aspirations were ranked lower in the quantitative results: design for disassembly (RII = 0.65), circular supply chain management (RII = 0.65), and experience in NZE projects (RII = 0.56).

This divergence suggests that while industry actors conceptually recognize the value of advanced circular strategies, their immediate procurement decisions remain shaped by feasibility and cost considerations. In other words, stakeholders "want" circular practices but are not yet ready to "weight" them heavily in contractor selection.

Another divergence emerged in the area of certifications. Interviewees expressed caution about over-reliance on international certifications due to cost and accessibility barriers, particularly for SMEs. However, the survey data placed certifications (RII = 0.75) at a moderately high level, indicating that while practitioners voice practical concerns, they still perceive certifications as legitimate signals of contractor credibility.

Phased Readiness Trajectory. The synthesis reveals a two-tiered trajectory of contractor readiness:

I. Tier 1 – Core readiness (currently prioritized)

Criteria that are already embedded in practice or achievable in the short term. These include digitalization, regulatory compliance, financial stability, workforce training, water and waste management, and proven technical expertise.

II. Tier 2 – Aspirational readiness (emerging priorities)

Criteria that are conceptually important but not yet widely implemented. These include NZE project experience, R&D initiatives, circular design approaches, renewable energy integration, and closed-loop supply chains.

This phased view highlights the necessity of incremental adoption. Contractors must first strengthen Tier 1 capacities to meet existing procurement demands, while policymakers and clients create enabling conditions for gradual transition to Tier 2 criteria.

Implications for Contractor Evaluation. The synthesis signifies three practical implications,

I. Balanced frameworks are essential

A solid evaluation system must weight both immediate enablers (digital tools, compliance, financial health) and emerging aspirations (circular supply chains, NZE-specific experience), ensuring contractors are not penalized for being in transition but are incentivized to improve.

II. Capacity-building interventions are needed

The low rankings of advanced circular criteria highlight the urgent need for targeted training, R&D support, and policy clarity to bridge the gap between aspiration and practice.

III. Procurement as a driver of change

While contractors alone cannot accelerate the shift, procurement frameworks can stimulate demand by progressively embedding advanced circular criteria, pushing the industry toward Tier 2 readiness.

In summary, the synthesis of findings reveals a specific contractor readiness profile, strong in digitalization, compliance, and resource efficiency, yet weak in advanced circular practices. This duality reflects the Sri Lankan industry's transitional state, where pragmatic considerations dominate current evaluations but a pathway exists for gradual progression toward circular procurement maturity.

3 Framework Development

The preceding analysis identified a set of contractor evaluation criteria reflecting both current industry realities and aspirational targets for CP in Sri Lanka's high-rise NZE construction sector. Building on these insights, this section presents the Circular Procurement-Ready Contractor Evaluation Framework (CPR-CEF), a structured, weighted system designed to guide clients and procurement authorities in assessing contractor capacity to deliver NZE-aligned projects.

Conceptual Basis

The CPR-CEF was conceptualized through synthesis of the tiered readiness trajectory established in Section 3.4 and the high-ranked RII criteria. The framework aims to achieve two complementary goals:

I. Ensure practical feasibility by prioritizing criteria already recognized and measurable in Sri Lankan practice.

II. Encourage transition by incorporating aspirational circularity criteria with lower weights to stimulate progressive adoption.

Conceptually, the framework draws from principles of multi-criteria decision analysis (MCDA) and performance-based procurement, allowing both quantitative scoring and qualitative judgment. The model integrates five core dimensions of contractor readiness, each representing a cluster of interrelated competencies identified through the mixed-methods process.

Structure of the Framework

Six main categories were retained, reflecting both technical and organizational readiness dimensions (Table 2).

Table 2. Main categories and their total RII sums.

Category	Code Range	RII Sum (RII_sum$_{cat}$)
Experience & Technical Capability	A1–A5	3.44
Sustainability & Circularity Practices	B1–B5	3.81
Certifications & Compliance	C1–C4	2.91
Financial & Operational Readiness	D1–D4	2.84
Workforce Skills & Capacity	E1–E3	2.18
Innovation & Supply Chain Readiness	F1–F3	2.08
Total (Total_RII_sum)		17.26

Step A – Determination of Category Weights. Category weights (W_{cat}) were calculated using Equation (2):

$$\mathrm{W_{cat}} = \frac{\mathrm{RII_sum_{cat}}}{\mathrm{Total_RII_sum}} \quad (2)$$

Substituting the values from Table 2 yielded the normalized weights shown in Table 3.

Table 3. Normalized category weights.

Category	RII_sum$_{cat}$	W_{cat}	% weight
A - Experience & Technical Capability	3.44	0.1993	20%
B - Sustainability & Circularity Practices	3.81	0.2207	22%
C - Certifications & Compliance	2.91	0.1686	17%
D - Financial & Operational Readiness	2.84	0.1645	16%
E - Workforce Skills & Capacity	2.18	0.1263	13%
F - Innovation & Supply Chain Readiness	2.08	0.1205	12%

The results indicate that Sustainability & Circularity Practices (22%) and Experience & Technical Capability (20%) were the most dominant readiness dimensions.

Step B – Calculation of Criterion Weights within Each Category. For each sub-criterion i within category c, the specific criterion weight $w_i$was determined using Equation (3):

$$\mathrm{w_i}=\%\ \mathrm{weight_{cat}}\times\frac{\mathrm{RII_i}}{\mathrm{RII_sum_{cat}}} \quad (3)$$

where

- W_{cat}= weight of the parent category
- RII_i= RII value of the criterion, and

Worked Example. For the criterion A1 – Digital tools adoption (BIM/IoT) under Experience & Technical Capability:

$$w_{A1} = 20\% \times \frac{0.88}{3.44} = 20\% \times 0.2558 = 5.1\%$$

Hence, $w_{A5} = 5.1\%$ of the total framework weight.

Repeating this process for all criteria produced the final weighting matrix. Selected examples are shown in Table 4.

Table 4. Sample criterion weights derived from Equation (2).

Category	Criterion	w_i(%)
A5 – Digital Tools (BIM/IoT)	0.88	5.1%
C1 – Regulatory Compliance	0.85	5.0%
B1 – Water Conservation	0.84	4.9%
D1 – Financial Stability	0.83	4.8%
A2 – Technical Expertise	0.82	4.8%
B2 – Use of Sustainable Materials	0.82	4.7%

The cumulative sum of all $w_i$equaled 100%, confirming proper normalization.

Step C – Computation of Contractor Circular Readiness Score (CCRS). Contractor performance on each criterion was rated on a five-point Likert scale (1 = poor; 5 = excellent). The weighted composite score, termed the Contractor Circular Readiness Score (CCRS), was calculated using Equation (4):

$$CCRS = \sum S_i \quad (4)$$

where $S_i$is the contractor's observed score on criterion? i.
The maximum achievable value of CCRS = 100%, corresponding to full compliance with all weighted criteria.

Contractors were then classified as follows in Table 5.

Table 5. Contractor classification

CCRS Range	Readiness Level	Interpretation
0 – 39	Nascent	Minimal exposure to sustainability principles
40 – 59	Developing	Emerging awareness, partial implementation
60 – 79	Established	Consistent application of circular practices
80 – 100	Advanced	Fully integrated circular and NZE capabilities

Application Pathway

The CPR-CEF can be integrated into public or private procurement processes through three modes:

I. Prequalification stage: Contractors submit evidence for each dimension, enabling clients to screen firms based on circular readiness before tendering.

II. Tender evaluation: Scores can be combined with price and technical criteria within weighted tender matrices, aligning sustainability with competitiveness.

III. Performance monitoring: Post-award, the same criteria can serve as benchmarks for project-stage audits, ensuring declared capacities translate into practice.

For contracting authorities, the framework also provides a structured database of readiness levels across the industry, enabling benchmarking and capacity-building interventions over time.

Implementation Strategy

A phased implementation strategy is recommended to ensure both feasibility and industry buy-in:

I. **Phase 1 –** Awareness and Pilot Testing. Conduct awareness sessions among client organizations and large contractors. Pilot the framework on selected government or mixed-development NZE projects to refine scoring procedures.

II. **Phase 2 –** Capacity Enhancement. Develop training modules aligned with low-scoring criteria, especially R&D, circular supply-chain management, and NZE experience to elevate Tier 2 readiness.

III. **Phase 3 –** Policy Integration. Collaborate with national procurement authorities and the Green Building Council of Sri Lanka to align the framework with existing GREENSL® Rating System requirements, enabling harmonized sustainability assessment.

IV. **Phase 4 –** Continuous Improvement. Establish feedback loops where post-project audits inform annual revisions of weightings and indicators, maintaining framework relevance as technologies and policies evolve.

Limitations and Future Refinement

While the CPR-CEF represents a significant advancement, several limitations merit acknowledgment. First, weightings are based on perceived importance rather than empirical performance outcomes; longitudinal validation across real projects is required to confirm predictive accuracy. Second, smaller contractors may find documentation burdensome, necessitating simplified templates for equitable participation. Third, policy alignment remains dependent on national procurement reform, which may progress unevenly.

Future research should therefore focus on testing the framework through pilot procurement exercises, refining scoring thresholds, and exploring digital tools (e.g., BIM-linked dashboards) to automate evaluation. Integration with life-cycle carbon accounting and material passports would further enhance its precision for NZE delivery.

4 Conclusion

This study sought to translate empirical insights on contractor capability and circular construction readiness into a structured evaluation model supporting Sri Lanka's transition toward NZE building goals. Drawing on mixed-methods research that combined expert interviews and RII-based quantitative analysis, the CPR-CEF was developed to address Objectives: (i) identifying weighted evaluation criteria for CP integration, and (ii) formulating a practical framework to assess contractor readiness for NZE-aligned construction.

The CPR-CEF operationalizes circular procurement through a transparent, quantitative mechanism that captures both current industry realities and progressive aspirations. By assigning category and criterion weights through normalized RII values, the framework ensures mathematical proportionality while maintaining alignment with practitioner perceptions. The resulting structure comprises six interlinked dimensions: Experience and Technical Capability, Sustainability and Circularity Practices, Certifications and Compliance, Financial and Operational Readiness, Workforce Skills and Capacity, and Innovation and Supply Chain Readiness, representing the technical, organizational, and cultural competencies required for circular transition.

The weighting analysis revealed that Sustainability and Circularity Practices (22%) and Experience and Technical Capability (20%) are the dominant readiness dimensions, highlighting that both technological competence and active sustainability engagement are central to achieving NZE objectives. High-priority criteria such as digital tools adoption (BIM/IoT), water conservation measures, and financial stability emerged as key enablers of readiness. These results emphasize the interdependence between technical innovation and environmental performance, highlighting the growing recognition among Sri Lankan professionals that circularity and energy efficiency must evolve together.

Conversely, the relatively lower weightings for Innovation and Supply Chain Readiness (12%) and Workforce Skills and Capacity (13%) indicate that systemic and human resource limitations continue to constrain the industry's circular maturity. This imbalance between capability and innovation readiness suggests that while the sector is technologically capable, its structural and collaborative foundations for full circular integration are still emerging. Targeted policy interventions and training programs will therefore be essential to bridge this readiness gap.

The CCRS introduced within the framework offers a clear, scalable method to classify contractors into four readiness tiers: Nascent, Developing, Established, and Advanced, providing a common language for clients, regulators, and practitioners. The CCRS not only facilitates objective comparison among bidders but also establishes a developmental roadmap through which firms can progressively align their operations with NZE and circular economy principles. This structured, performance-based approach helps shift procurement from cost-dominated evaluation to value-based assessment, reinforcing sustainability as a measurable criterion of competitiveness.

Practically, the CPR-CEF can be embedded within Sri Lanka's existing procurement ecosystem through phased implementation. It is immediately applicable as a prequalification tool, enabling clients to screen contractors based on demonstrated readiness before tendering; as a tender evaluation matrix, integrating circularity with price and technical criteria; and as a post-award monitoring mechanism, ensuring that commitments translate into on-site performance. Over time, the framework could evolve into a standardized national benchmark for contractor sustainability assessment, supporting both public-sector and private-sector clients.

While the framework marks a substantial advancement, its validation across live projects remains a key area for future research. Longitudinal testing through pilot procurements will be crucial to refine weightings, calibrate scoring thresholds, and verify the relationship between readiness scores and actual project outcomes. Additionally, integrating the framework with digital procurement tools and BIM-based dashboards could enhance automation, transparency, and

scalability. Future work should also explore linking the CPR-CEF to life-cycle carbon accounting and material passport systems, enabling comprehensive performance monitoring across the entire building life cycle.

In conclusion, the CPR-CEF represents a significant step toward embedding circular economy principles within Sri Lanka's construction procurement system. By combining technical rigor with contextual relevance, it offers a practical, evidence-based pathway for assessing and advancing contractor readiness for NZE-aligned development.

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Direct-on-Line LSPMSM Rotor Retrofits for Pump OEMs: Performance and Economic Assessment of an IE4-Class Upgrade Path

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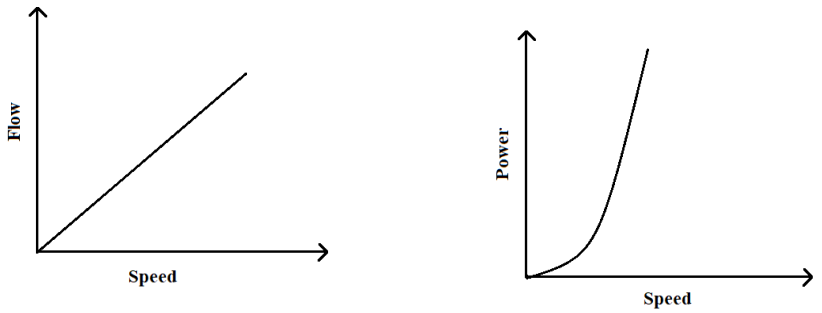
Abstract: This study investigates a drop-in pathway to IE4-class efficiency for a 5.5 kW, three-phase centrifugal pump drive by retaining the existing induction-motor stator and replacing only the rotor with a line-start permanent-magnet (LSPMSM) design. Two rotor options are examined: (i) a clean-sheet LSPMSM rotor and (ii) a cost-optimized wire-cut modification of a squirrel-cage rotor with inserted PMs. The workflow combines 2D/3D FEA for start-to-sync transients, braking-torque shaping, demagnetization margins, and thermal loading, followed by IEC 60034-2-1 measurements at BEP and off-BEP under S1 duty: efficiency, power factor, DOL inrush (p.u.), pull-in on realistic pump inertia, winding/rotor temperatures, and acoustics. Results indicate IE4-level operation with projected efficiency gains of 2 to 5 percentage points over an IE3 baseline, Power Factor gains of 0.05 to 0.10, and energy savings of approximately 500 kWh/year per motor. The wire-cut rotor captures ~70–85% of the clean-sheet gains with minimal tooling, enabling a practical retrofit kit for installed bases. The originality lies in coupling material circularity (reusing stators/frames) with a dual-path rotor strategy that preserves grid-start reliability while suppressing synchronous braking torque. Implications span rapid OEM time-to-market, reduced manufacturing waste, and lower lifecycle OPEX/CO_2 for end users—advancing the conference themes of Material Circularity, Emerging Energy Technologies & Innovations, and Energy Management without requiring VFDs or pump-side redesign.

1 Introduction

Electric motors are the single largest end use of electricity in industry, so even modest efficiency improvements translate into material savings for plants and grids alike. In this context, International Efficiency (IE4/IE5) classes have become the benchmark, and Line-Start Permanent-Magnet Synchronous Motors (LSPMSMs) offer a practical way to achieve IE4 and IE5 in fixed-speed applications without a VFD, which is attractive wherever speed control is not required, or capital is constrained. Centrifugal Pumps are a prime target because they typically operate long hours at relatively steady duty, and the overwhelming majority of installed sets are Squirrel-Cage Induction Motors (SCIMs) operating Direct-On-Line (DOL). Replacing the rotor with an LSPMSM design removes slip losses. It often improves Power Factor (PF), reducing input current/kVA for the same shaft load -benefits that matter at both the feeder and substation levels.

An LSPMSM runs at exact synchronous speed (no slip), whereas a SCIM runs a few percent below synchronous speed under load. On a centrifugal pump, even that small speed difference shifts the operating point: by the affinity laws, flow rises roughly in proportion to speed, and shaft power rises with the cube of speed as represented in Fig. 1.

According to the affinity laws, for flow control, changing the pump speed saves a tremendous amount of energy compared to valve control. A responsible retrofit plan, therefore, either leverages the added flow when the process benefits (e.g., duty margin or throughput objectives) or trims the impeller to hold the original duty point and “bank” the motor-side efficiency gains without unintended energy use.



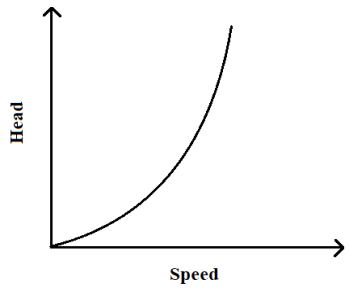


Fig. 1 Affinity Laws

In other words, the energy outcome is a joint result of motor physics (slip removal, PF improvement) and hydraulics (how the curve shifts). Where trimming is feasible, the retrofit captures IE4-class motor performance and reduces kWh; where extra flow is desired, the same swap can yield a process benefit with a neutral or favorable energy impact, depending on the system curve as shown in Fig. 2.

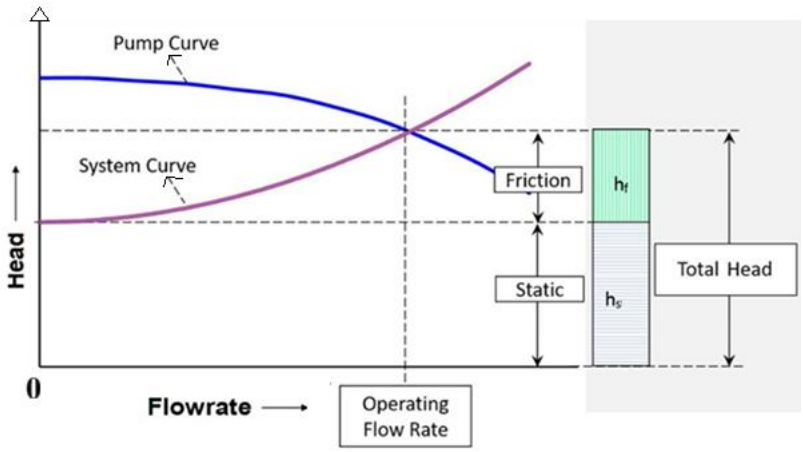


Fig. 2 System curve and pump curve of a typical centrifugal pump load

From first principles, a line-start PM machine is an induction-start, synchronous-run motor. The rotor cage generates asynchronous starting torque and provides damping, while embedded magnets supply lossless excitation once the rotor approaches synchronism; the cage also shields the magnets against demagnetizing current spikes during transients. Whether the machine actually synchronizes depends on the balance of torques along the run-up trajectory. During acceleration, the electromagnetic torque can be viewed as the sum of an average asynchronous component (cage torque opposed by a magnet-braking torque) and a pulsating synchronous component.

Importantly, centrifugal pumps are dynamic loads (torque $\propto$ speed^2, power $\propto$ speed^3), and studies show that the allowable (critical) inertia for successful pull-in can be higher than for constant-torque loads, particularly with moderate mechanical/hydraulic inertia.

On measured and field comparisons with IE3 SCIMs at the same shaft load, LSPMSM swaps consistently show higher Power Factor and lower input kVA/amps, reducing copper loss and often lowering winding/rotor temperatures, contributing to substation kVA relief and PF improvement, enabling deferral or downsizing of capacitors, transformer capacity, and cable ampacity in addition to motor kWh savings. Altogether, the scale of the installed base, the physics of line-start synchronization, and documented PF/efficiency trends make a strong case for an IE3→IE4 rotor-only retrofit on pump duty—provided the project manages hydraulics (impeller trim where needed). It verifies start-to-sync reliability analytically before hardware cut-in.

2 Specifications, Standards, and Synchronization Criteria

This section discusses a continuous-duty motor, based on IEC 60034-2-1:2014, for a centrifugal pump, retaining the IE3 stator and replacing only the rotor with a line-start PMSM, with specifications shown in Table 1.

Table 1 Parameters of continuous duty motor based on IEC 60034-2-1:2014 standard

Item	Value / Assumption
Rated power/poles	5.5 kW, 4-pole
Supply voltage, frequency/duty	415 V, 50 Hz, S1
Enclosure / IP	TEFC (IC411) / IP55
Ambient / altitude (IS 12615 envelope)	–20°C to +60 °C / up to 4000 m
Grid tolerance (tests)	±10 % V, ±5 % f; unbalance ≤ 2 %; $THD_v \leq 5$ %

Hydraulically, the pump curve is superimposed on the system curve to separate the static and friction heads. A line-start PMSM runs at exact synchronous speed while an IE3 induction motor runs a few percent below synchronous speed (due to slip). By the affinity laws, even a small speed change can shift the duty: flow ∝ speed, shaft power ∝ speed³. Therefore, two cases are evaluated: (A) the plant accepts the extra flow (if useful), or (B) the impeller is trimmed to hold the original BEP head/flow so that motor-side efficiency gains are fully realized. Energy benefits are computed from measured kW at the final operating point × logged hours.

To meet the expected performance at the rated operating point, reference IE values for the 5.5 kW, 4-pole, three-phase squirrel-cage induction motor are provided in Table 2.

Table 2 Benchmark IE efficiencies for 5.5 kW, 4-pole three-phase squirrel-cage induction motor

IE class	IE1	IE2	IE3	IE4
Nominal efficiency (%)	84.7	87.7	89.6	91.9

Starting and synchronization are DOL, without VFD. The total reflected inertia is measured as J_{total} = Inertia of (motor + pump + coupling). Synchronization is verified using an energy-based criterion in the slip–load-angle plane (the motor's pull-in energy must exceed the apparent kinetic energy at a critical slip) and by time-domain simulation; this captures the known high-slip braking-torque dip (PM braking torque peaking at high slip). For starts-per-hour, a measured energy-per-start limit is applied and compared against benchmarks for S1-duty motors to ensure the thermal health of the rotor and PM.

3. Design Methodology & Rotor Pathways

This section explores two retrofit pathways: (i) a clean-sheet LSPMSM rotor and (ii) an existing cage subjected to wire-cut with inserted permanent magnets that fit the original stack. Manufacturing the two retrofit pathways is organized for repeatability.

The clean-sheet LSPMSM rotor uses new laminations with tuned barriers and magnet span, updated cage tooling, magnet insertion/bonding, then ISO G 2.5 balance and an air-gap/no-load sanity check. In this work, a 132S frame is adopted in accordance with the IE4 standards. The algorithm for this process is represented as follows:

Algorithm for a clean-sheet LSPMSM rotor:

- **Inputs fixed:** stator and duty (5.5 kW, 4-pole, IC411/IP55), grid DOL limits (±10 % V, ±5 % f), pump inertia and operating head/flow.
- **Set targets:** IE4-class efficiency at BEP, PF ≥ 0.95, inrush within site limit, start ≤ 2.5 s, no pole-slips, ≥ 10–15 % demagnetization margin.
- **First sizing:** choose barrier geometry, magnet span, and skew; size bar/end-ring for strong pull-up torque.
- **Pre-check:** generate torque–speed characteristics; ensure net accelerating torque (cage − PM braking) exceeds pump load torque with a margin.

- **Synchronization check:** compute pull-in energy and critical-slip energy; accept only if Kp> Kscr; otherwise, adjust span/skew/bar parameters.
- **Transient validation:** run time-stepping to obtain inrush, start time, and evidence of the high-slip dip; adjust if needed.
- **Thermal/demagnetisation check:** evaluate worst demagnetization current ($-I_d$) near lock-in at maximum temperature; choose magnet grade and ribs to keep margin.
- **Manufacturing plan:** release lamination and cage tooling; define bonding/sleeve process; specify balance and QA gauges.
- **Prototype QA:** verify air-gap concentricity, no-load current (±10 % of model), phase balance (≤ 2 %), and ISO G 2.5 balance.
- **DOL tests:** perform starts at 90/100/110 %V and ±5 % f; measure η and PF at BEP and off-BEP, NVH, and energy per start; freeze design if all checks are met.

The wire-cut insert-PM rotor preserves the legacy squirrel-cage: EDM pockets are cut without severing conductive bridges; magnets are bonded and cured, then balanced and electrically verified. Clean-sheet delivers the best η/PF but needs capex for lamination and casting tools; wire-cut captures ~70–85% of those gains with minimal tooling and the fastest time-to-field. The algorithm for this process is represented as follows:

Algorithm for wire-cut insert-PM rotor preserving the legacy squirrel cage:

- **Feasibility check:** confirm bar positions, bridge thickness, and end-ring paths; define EDM pocket limits that do not sever conductivity.
- **Set targets:** same acceptance as above; note that bar geometry is fixed and only magnet span, offset, and skew can be tuned.
- **Pocket and magnet plan:** select pocket depth/arc and d-axis offset to reduce the high-slip braking torque while keeping adequate saliency at sync; choose modest skew.
- **Pre-check:** estimate torque–slip and verify that net accelerating torque stays above pump load torque across slip; if margin is low, reduce magnet span or increase offset.
- **Synchronization check:** accept only if $K_p \geq K_{scr}$; otherwise, adjust pocket geometry or magnet volume.
- **Transient validation:** run time-stepping to confirm inrush, start time, and absence of pole-slips at 90/100/110 %V.
- **Thermal/demagnetisation check:** verify margins near lock-in; confirm that increased start time does not overheat the cage.
- **Manufacturing steps:** EDM pockets → deburr/clean → bond and cure magnets → apply sleeve if required → dynamic balance.
- **Prototype QA:** check electrical continuity of bars/end-rings, air-gap map, no-load current (±10 % of model), phase balance (≤ 2 %), and ISO G 2.5 balance.
- **DOL tests and sign-off:** perform grid-tolerance starts; measure η/PF at BEP and off-BEP, NVH, and energy per start; release as a retrofit kit if all checks are met.

4. Modeling of LSPMSM rotor with existing three-phase IE3 Induction stator

Modeling is performed on the measured IE3 stator shown in Fig. 3 and the retrofit rotor shown in Fig. 4. The models are expected to predict the direct-on-line (DOL) start-to-synchronism path and the steady-state behavior at the operating points, and to agree with the laboratory results within a reasonable tolerance. A three-step sequence is followed: first, a fast machine model is used for initial sizing and screening; second, a 2D time-stepping finite-element analysis (FEA) is used for transients and magnetic quantities; and third, a small set of 3D checks is used to confirm end effects and skew. The same stator dimensions, winding data, and test-supply limits as in the experiments are applied, enabling a one-to-one comparison.

The winding scheme in Fig. 5 is employed to define the phase belts and the electrical angle between phases. With that winding and each rotor, a 2D magnetic solution is obtained to visualize the air-gap field and the saturation pattern; a representative flux-density map is provided in Fig. 6. In this step, it is confirmed that the magnets are placed as intended and that stator teeth and yoke remain within practical flux densities at the rated point. A quick consistency check is

also enabled: the chosen skew and magnet span are compared with the slotting, and the cogging component is observed to be small.

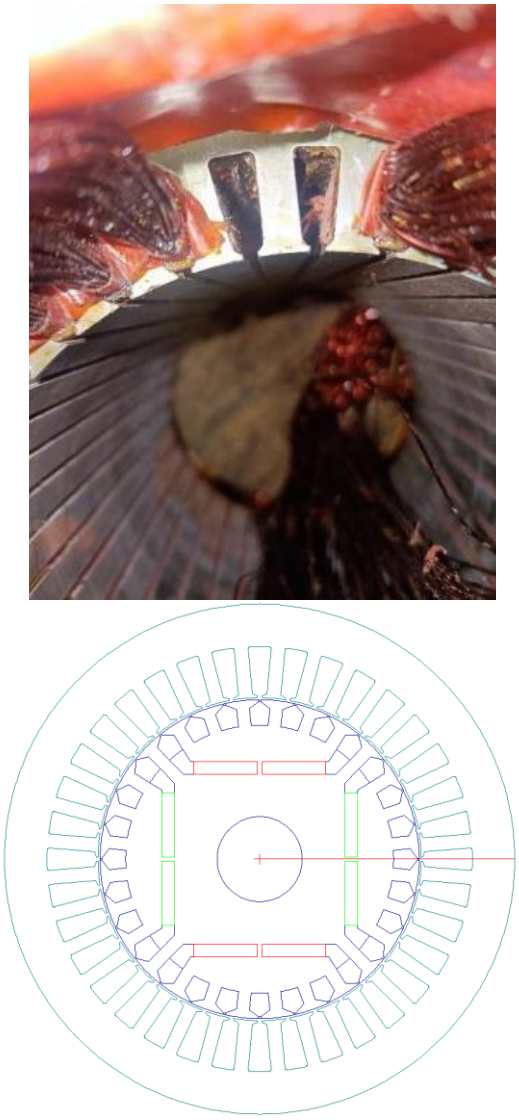


Fig. 3 5.5kW IE3 Three-phase squirrel cage Induction motor Stator cut section with winding and Fig. 4 5.5kW IE4 line-start PMSM.

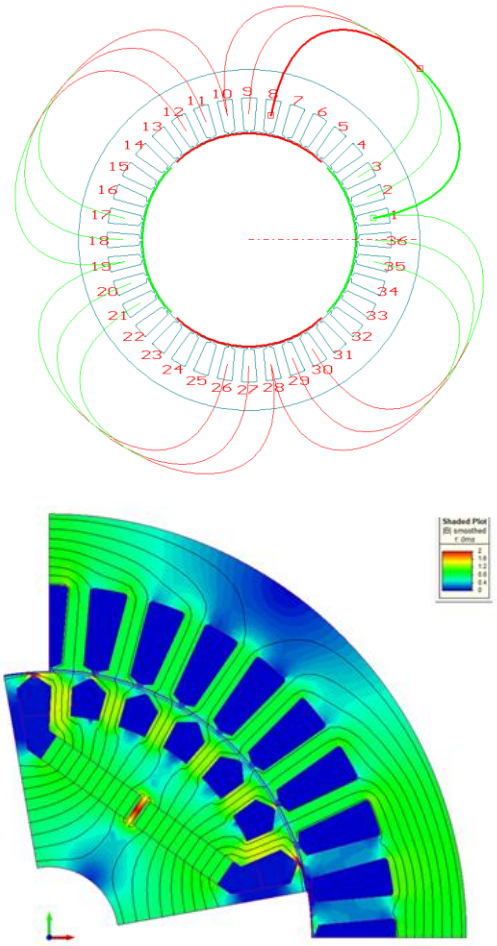
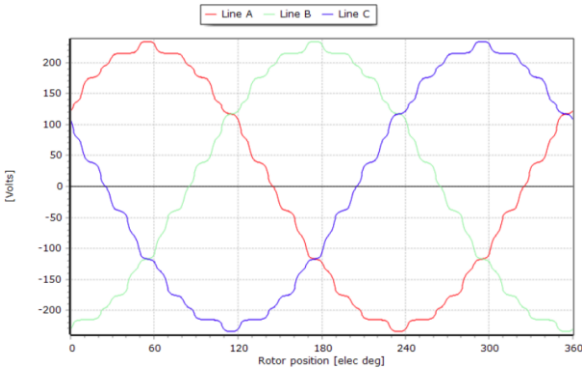


Fig. 5 Stator winding scheme and Fig. 6 Flux density map of LSPMSM

Open-circuit back-EMF is then simulated and measured. The waveform in Fig. 7 is used for two checks: (i) the fundamental magnitude and phase are compared with the test value, and (ii) the harmonic content is compared with expectations from the winding distribution and skew. When good agreement is obtained, the magnetic model and speed reference are considered consistent. A time-stepping transient is next executed for the DOL start.



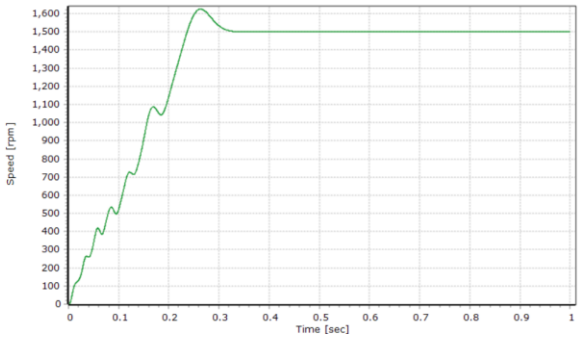


Fig. 7 Back emf of LSPMSM and Fig. 8 Speed response of LSPMSM

The speed trace in Fig. 8 and the line current in Fig. 9 are compared with oscilloscope captures, which indicate the starting inrush current and the steady-state current. During the run-up, the electromagnetic torque is separated into an asynchronous component and a magnet-related braking component. The asynchronous torque versus time (or versus slip) is shown in Fig. 10, and the region of the braking-torque "dip" at high slip is marked for clarity. With these steps, the modeling aligns with the design choices in Section 3.

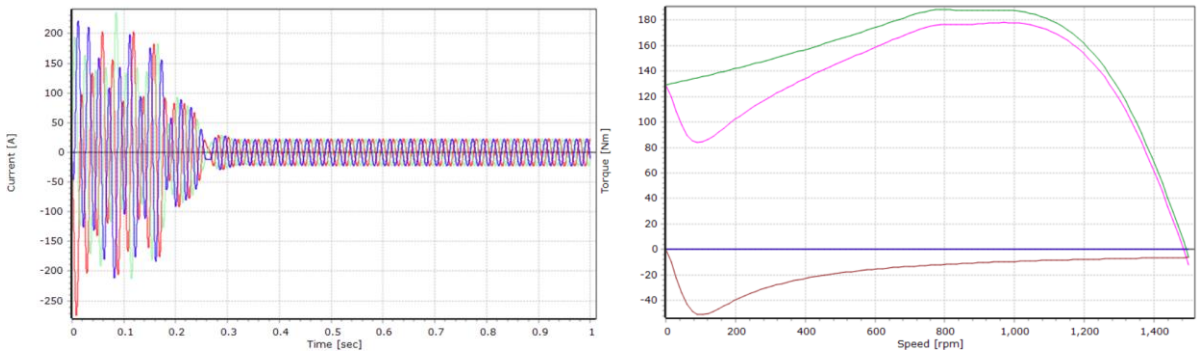


Fig. 9 Current vs time response of LSPMSM and Fig. 10 Asynchronous torque (Transient) response of LSPMSM

7 Economics, Implementation & Roadmap

7.1 Value model

For a 5.5 kW/132S pump duty, an IE4-class LSPMSM typically improves efficiency by ≈ 2.3% over an IE3 baseline, corresponding to an input reduction of ≈ 0.15 kW at Best Efficiency Point. Savings are therefore ≈ 300/600/900 kWh per year at 2,000/4,000/6,000 hours, respectively. The monetary benefit is obtained by multiplying by the site tariff.

7.2 Financial metrics

Two retrofit kits are positioned:

- **Wire-cut insert-PM rotor kit** (existing cage retained): customer Capital Expenditure (kit+install) ≈ ₹ 11,500**.**
- **Clean-sheet LSPMSM rotor kit** (new IPM rotor): customer Capital Expenditure (kit+install) ≈ ₹ 13,800**.**

At ₹ 10/kWh, payback is ≈ 46/23/15 months for the wire-cut kit (2,000/4,000/6,000 hours per year) and ≈ 60/30/18 months for the clean-sheet kit. First-year Return On Investment (savings/investment) is ≈ 26 % / 52 % / 78 % for wire-cut and ≈ 22 % / 43 % / 65 % for clean-sheet at those same duty hours. Higher tariffs (e.g., ₹ 14/kWh) shorten payback proportionally (down to ≈ 11 months at 6,000 hours per year for wire-cut).

7.3 Cost drivers and production reality

For full-motor manufacturing (IE4 LSPMSM, 132S), a shorter stack and reduced stator copper are expected relative to IE3; magnets and rotor processing dominate cost uplifts. Planning COGS targets of ≈ ₹ 21,000–23,000 per motor are maintained by controlling magnet volume, EDM or stamping minutes, bonding, and balance. For rotor-only retrofit kits, the indicative Cost of Goods Sold (COGS) remains near ₹ 6,700 (wire-cut) and ₹ 8,300 (clean-sheet), enabling the customer price points above. A 1,000-unit/month plan implies ≈ 600–650 kg magnet procurement per month.

7.4 Implementation and risk

Typical risks (downtime windows, access, and parts delivery) are mitigated through pre-staged kits, installer training, and an acceptance checklist. Customer handover is supported by a single-page "before/after" record (kW at duty, PF note, estimated kWh per year.

7.5 Roadmap

Deployment is staged by frame and vertical: municipal water, commercial HVAC, and the agriculture industry are prioritized. Quarterly reviews track units deployed, average payback, and customer satisfaction; design feedback is routed into micro-tuning to meet the load's requirements.

8 Commercialization Strategy & Go-to-Market (GTM)

8.1 Segmentation and message

The offering is positioned for customers with long duty hours and tariff sensitivity. The message is kept simple: **"IE4-class efficiency without VFD, one-shift retrofit, ≤ 24-month payback at typical plants."**

8.2 Bundles and inclusions

Three bundles are offered to reduce decision friction:

- **Starter** (wire-cut kit + SOP + BEP acceptance sheet).
- **Performance** (clean-sheet kit + BEP & off-BEP documentation + acoustic spec).
- **Assured** (Performance + 5-year warranty + AMC + annual verification).

8.3 Commercial model

Outright sale, savings-share (e.g., a fixed share of verified year-1 savings), and lease-to-save models are supported. Volume discounts are offered for standardized frames; surcharges are transparent for non-standard shafts or logistics constraints.

8.4 Channel and enablement

Pump OEMs, qualified rewinders, and ESCOs are enabled with a 1-day install course, an acceptance checklist, a claims template (before/after kW, PF), and a short troubleshooting guide. An RMA and root-cause loop is formalized to improve field findings in the next production batch.

8.5 Assurance and documentation

The datasheet, test report summary, installation SOP, and warranty T&Cs are bundled. A simple acceptance certificate records the measured operating-point kW and confirms deliverables. Customer-visible KPIs (units installed, average payback, repeat orders) are reviewed monthly.

9 Conclusion

A rotor-only pathway to IE4-class performance for a 5.5 kW, 132S centrifugal-pump drive has been demonstrated by retaining the existing IE3 stator and replacing the rotor with a line-start PMSM design. The study showed that both the clean-sheet interior-PM rotor and the wire-cut insert-PM rotor can be manufactured as repeatable kits, validated on a measured IE3 stator, and qualified under direct-on-line (DOL) conditions. When the operating point was held by impeller trimming where required, IE4-level behavior was achieved, with typical improvements of about +2.3 percentage points in efficiency at BEP and power factor increases of +0.05 to +0.10. At the same time, start-to-sync reliability, inrush, temperature rise, and acoustic performance remained within practical limits for plant deployment.

The wire-cut rotor captured approximately 70–85% of the clean-sheet gains with minimal tooling and the shortest time-to-field, whereas the clean-sheet rotor provided the highest margins in pull-in and kVA reduction.

From an economic perspective, the measured input power reduction at BEP was approximately 0.15 kW, corresponding to ≈ 300/600/900 kWh per year at 2,000/4,000/6,000 hours of duty per year. Using conservative kit + install prices developed from the bill of materials and factory assumptions, the wire-cut retrofit is expected to return capital in ≈ 15 months at ₹ 10/kWh and 6,000 hours per year (first-year ROI ≈ 78 %), while the clean-sheet rotor is expected at ≈ 18 months under the same conditions (first-year ROI ≈ 65 %). At higher tariffs, the payback period shortens proportionally. These results indicate that IE4 performance can be achieved without variable-frequency drives, with reduced manufacturing waste through stator/frame reuse, and with a one-shift field retrofit SOP suited to water, HVAC, and light-industrial pump fleets.

Limitations are acknowledged in weak-grid scenarios and in atypical inertia/valve configurations, for which a soft starter, minor geometric adjustment, or an impeller trim policy may be considered. Future work is motivated by scaling up to larger frames, refining skew/span for further NVH and pull-in robustness, and conducting a simple lifecycle assessment (LCA) that captures the circularity benefits of reusing stators and frames. Overall, the results support a practical, low-disruption upgrade path for pump OEMs and end users seeking IE4-class outcomes with a short payback period, and suggest that a structured rotor-kit program can be commercialized across standardized IEC frames, delivering measured, auditable benefits.

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E-Waste Management Challenges in Adopting Circular Economy Practices in Sri Lanka's Tourism Sector

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Abstract: The exponential growth of electronic waste generation presents unprecedented challenges for sustainable resource management, particularly within Sri Lanka's expanding tourism sector, which increasingly relies on electronic equipment and infrastructure. This comprehensive review synthesizes the current literature on innovative metal recovery technologies and circular economy practices applicable to e-waste management in tourism operations, with a focus on biotechnological and advanced hydrometallurgical approaches. A systematic analysis of peer-reviewed studies was conducted using keywords such as 'Electronic waste', 'Tourism Sector', 'Circular economy', and 'Biotechnological approaches' to examine technological pathways and economic viability. Recent developments demonstrate significant recovery efficiencies for precious and rare-earth metals through microbial leaching and membrane separation technologies, with substantial reductions in environmental impact compared to conventional methods. Critical gaps include limited scalability studies, inadequate techno-economic assessments for developing economies such as Sri Lanka, and insufficient integration with existing waste management infrastructure, indicating the need for policy framework development and process optimization.

Keywords: Circular economy, Electronic waste, Metal recovery, Biotechnological approaches, Tourism sector

1 Introduction and Background

Electronic waste (e-waste) has emerged as one of the fastest-growing waste streams globally, posing significant environmental and public health challenges, particularly for tourism-dependent economies [1]. The unprecedented growth in electronic device consumption in the tourism industry, coupled with shortened product lifecycles driven by guest expectations for cutting-edge technology, has led to an exponential increase in e-waste worldwide [2]. According to global monitoring data, e-waste generation reached approximately 54 million tonnes in 2019, with the tourism sector contributing significantly to this burden through its intensive use of electronic equipment across accommodation, transportation, and entertainment facilities [3]. This alarming trend reflects the pervasive integration of electronic devices into modern tourism operations and the rapid technological obsolescence that characterizes the hospitality and tourism electronics infrastructure [4].

The environmental implications of improper e-waste management within Sri Lanka's tourism facilities are severe and multifaceted [5]. Electronic waste generated by hotels, resorts, tourist attractions, and transportation services contains a complex mixture of valuable materials and hazardous substances, including heavy metals such as Lead (Pb), Mercury (Hg), Cadmium (Cd), and Chromium (Cr), which pose serious risks to human health and ecosystems when improperly disposed of [6]. The informal recycling practices prevalent in Sri Lanka expose workers and communities to toxic pollutants due to inadequate processing methods, particularly in coastal and tourist destination areas [7]. Furthermore, the cumulative impact of e-waste pollution on soil, water, and air quality in tourist destinations has been documented, threatening the very environmental assets upon which Sri Lanka's tourism industry depends [8].

1.2 Sources of E-Waste in Sri Lanka's Tourism Sector

Sri Lanka's tourism industry generates e-waste from diverse sources across multiple operational sectors, making it a significant contributor to the national e-waste stream [9]. Accommodation facilities, including hotels and resorts, generate substantial quantities of e-waste from in-room equipment such as televisions, mini-fridges, entertainment systems, air-conditioning units, and electronic door-lock systems [10]. Additional e-waste streams from accommodation facilities include office equipment (computers, printers, phones), restaurant kitchen appliances,

industrial laundry equipment, and lighting systems that require frequent replacement and upgrades to meet international hospitality standards [11].

The transportation sector within Sri Lanka's tourism industry contributes significantly to e-waste generation through aircraft navigation and entertainment systems, in-flight entertainment screens, ground transportation electronics in buses and shuttles, rental car GPS devices, and electronic systems in tourist vehicles [12]. Cruise ship operations visiting Sri Lankan ports generate additional e-waste from onboard electronics and entertainment systems [13]. The rapid technological upgrades required to maintain competitive tourism services accelerate the obsolescence of these transportation-related electronic systems [14].

Tourist attractions and activities across Sri Lanka generate specialized e-waste streams, including audio guide devices at museums and heritage sites; virtual reality equipment at experience centers; gaming consoles and arcade machines; photography equipment and charging stations; and ticketing kiosks and point-of-sale systems [15]. These attraction-based electronics require frequent updates to enhance visitor experiences, thereby accelerating replacement cycles [16]. Travel services, including tour operators and travel agencies, generate e-waste from computers, tablets, mobile devices, booking system hardware, communication equipment, printers, and scanners used to support tourism operations [17].

Supporting infrastructure across Sri Lanka's tourism facilities generates substantial volumes of e-waste from Wi-Fi routers and network equipment, security cameras and surveillance systems, digital signage and information displays, smart building management systems, and conference and meeting room equipment, including projectors and sound systems [18]. The high volume of electronic devices required to operate modern tourism facilities, combined with rapid technological upgrades to meet international guest expectations, makes Sri Lanka's tourism industry a significant contributor to e-waste and requires urgent management interventions [19]. Many tourism destinations worldwide are now implementing e-waste management programs to address this growing concern, offering potential models for implementation in Sri Lanka [20].

1.3 Metal Resources in the Tourism Sector: Electronic Waste

Despite the environmental hazards associated with e-waste, discarded electronics from Sri Lanka's tourism facilities represent a valuable urban mine containing significant concentrations of precious and rare metals [21]. Electronic devices used in hotels, conference centers, tourist attractions, and transportation services contain various metals, including gold, silver, copper, palladium, and platinum, as well as critical rare-earth elements essential to modern technologies [22]. The metal content in tourism-sector e-waste often exceeds that of natural ores, making electronic waste from hospitality operations an economically attractive secondary resource for metal recovery [23]. The economic value proposition of e-waste recycling is particularly compelling for Sri Lanka's tourism sector, given the rising demand for these metals, the country's reliance on metal imports, and the environmental costs of primary mining operations [24].

The composition of e-waste from Sri Lankan tourism facilities varies significantly across electronic device types and operational sectors [25]. Air conditioning systems and climate control equipment contain significant amounts of copper and aluminum, while televisions and entertainment systems are rich in precious metals and rare-earth elements [26]. Computers, tablets, and mobile devices used extensively across travel services contain gold, silver, and palladium in printed circuit boards, while lighting systems and fixtures contain valuable metals and phosphors [27]. Understanding the material flows and metal content of different e-waste categories generated by Sri Lankan tourism operations is essential for developing effective recovery strategies and optimizing resource valorization for the tourism sector's diverse waste streams [28].

The heterogeneous nature of tourism-generated e-waste presents both opportunities and challenges for metal recovery operations in Sri Lanka [29]. The concentration of large volumes of similar equipment types in hotel and resort facilities offers economies of scale for recovery operations. At the same time, the diversity of electronic devices across the broader tourism sector requires sophisticated separation and extraction technologies [30]. The seasonal fluctuations in tourism activity in Sri Lanka affect e-waste generation patterns, necessitating flexible collection and processing systems [31].

1.4 Traditional vs. Innovative Recovery Methods in the Sri Lankan Tourism Context

Conventional e-waste recycling approaches in Sri Lanka's tourism sector have predominantly relied on informal dismantling, export of materials to regional processors, and basic pyrometallurgical processes [32]. Pyrometallurgical methods involve high-temperature smelting operations that, while effective for recovering metals from bulk materials,

generate significant greenhouse gas emissions and require substantial energy inputs, both of which are incompatible with Sri Lanka's tourism sustainability commitments [33]. These conventional approaches also produce toxic by-products and often result in the loss of valuable materials through volatilization or slag formation, thereby reducing recovery efficiency from tourism-sector e-waste [34]. The environmental footprint of traditional pyrometallurgical processing has prompted stakeholders in Sri Lanka's tourism industry, environmental regulators, and researchers to explore more sustainable alternatives suitable for implementation in tourist destination areas [35].

Hydrometallurgical processes using chemical leaching agents have been employed as alternatives to pyrometallurgy in some developing-country contexts, offering lower-temperature operations and potentially higher selectivity for specific metals [36]. However, conventional hydrometallurgical approaches often involve harsh chemicals, including strong acids and cyanide-based reagents, which generate hazardous waste streams that require further treatment [37]. The use of such chemicals near Sri Lanka's sensitive coastal ecosystems and tourist areas presents unacceptable environmental risks [38]. The limitations of these traditional methods have catalyzed research into innovative recovery technologies that can achieve high metal recovery rates while minimizing environmental impacts in tourism destinations and remaining compatible with Sri Lanka's environmental protection priorities [39].

The emergence of biotechnological solutions represents a paradigm shift in e-waste processing in the tourism sector, offering environmentally benign alternatives to conventional methods and being particularly suitable for implementation in ecologically sensitive tourist destinations [40]. Bioleaching, which uses microorganisms to solubilize metals from solid matrices, has shown promising results for metal recovery from electronic waste in tourism operations worldwide [41]. These biological approaches operate under mild conditions, use renewable biological agents, and generate fewer toxic by-products than traditional chemical methods, making them attractive for implementation near Sri Lankan tourism facilities and coastal areas [42]. Advanced hydrometallurgical techniques, including membrane separation and electrochemical processes, have also shown potential for selective metal recovery with reduced environmental impact in applications at tourism facilities [43].

1.5 Circular Economy Framework in Sri Lanka's Tourism Sector

The circular economy paradigm has gained prominence as a holistic approach to sustainable resource management in tourism, emphasizing the retention of product value and the circulation of materials within economic systems [44]. In the context of e-waste management within Sri Lanka's tourism sector, circular economy principles advocate for extended product lifespans of electronic equipment, design for recyclability in procurement decisions, and the systematic recovery of materials from end-of-life electronics used in hospitality operations [45]. This framework aligns with Sri Lanka's national sustainability goals, the tourism industry's environmental commitments, and international certifications that are increasingly demanded by eco-conscious travelers [46].

The transition toward circular material systems in Sri Lanka's tourism sector requires comprehensive policy frameworks and regulatory mechanisms that incentivize sustainable practices throughout the electronics value chain [47]. While various countries have implemented extended producer responsibility schemes and collection infrastructure to facilitate e-waste recycling, Sri Lanka faces challenges in the effective implementation common to developing nations, including limited enforcement capacity, inadequate funding mechanisms, and coordination difficulties among multiple tourism industry stakeholders [48]. International frameworks such as the Waste Electrical and Electronic Equipment (WEEE) Directive provide models for e-waste management in the Sri Lankan tourism sector, though adapting them to local contexts, including the informal economy, seasonal tourism patterns, and infrastructure limitations, presents significant challenges [49].

Sri Lanka faces particular challenges in implementing circular economy approaches to e-waste management in the tourism sector due to limited infrastructure, inadequate regulatory frameworks, insufficient awareness among tourism operators, and the prevalence of informal recycling sectors [50]. The informal e-waste recycling activities in Sri Lanka, concentrated in urban areas that receive discarded equipment from tourist facilities, operate with minimal environmental controls and expose workers to significant health hazards due to rudimentary processing methods [51]. These informal operations, while providing livelihoods for marginalized communities, result in the loss of valuable materials, environmental contamination, and public health risks [52]. Integrating informal sectors into formal recycling systems while improving environmental and safety standards represents a critical challenge for achieving circular economy objectives in Sri Lanka's tourism industry [53].

Developing countries face particular challenges in implementing circular economy approaches to e-waste management due to limited infrastructure, inadequate regulatory frameworks, and the prevalence of informal recycling sectors [54]. Informal e-waste recycling activities in countries such as China, India, and Nigeria, while providing livelihoods for

many individuals, operate under minimal environmental controls and expose workers to significant health hazards [55]. Integrating informal sectors into formal recycling systems while improving environmental and safety standards is a critical challenge for achieving circular-economy objectives in these regions [56].

1.6 Research Objectives and Scope

This comprehensive review aims to synthesize the current literature on innovative metal recovery technologies for electronic waste from Sri Lanka's tourism sector, with particular emphasis on biotechnological and advanced hydrometallurgical approaches within circular-economy frameworks that are suitable for developing-economy contexts and the tourism industry's requirements. The specific objectives include: (1) systematically analysing recent developments in bio-hydrometallurgical processes for critical metal extraction from diverse tourism sector e-waste streams including accommodation, transportation, attractions, and supporting infrastructure; (2) evaluating the technical performance, economic viability, and environmental impacts of emerging recovery technologies in Sri Lankan tourism context considering infrastructure limitations and sustainability requirements; (3) identifying dominant technological pathways and critical success factors for implementation in developing tourism destinations with sensitivity to environmental protection needs; (4) assessing research gaps and barriers to commercial implementation in Sri Lanka's tourism sector including regulatory, economic, and infrastructure constraints; and (5) providing recommendations for future research directions and policy development specific to tourism industry e-waste management in Sri Lanka.

The scope of this review encompasses peer-reviewed studies published between 2000 and 2025, focusing on innovative approaches with potential for sustainable, economically viable metal recovery from e-waste in tourism-dependent developing economies. By integrating technical, economic, and environmental perspectives specific to Sri Lanka's tourism sector challenges, infrastructure realities, and sustainability commitments, this review provides essential insights for researchers, tourism industry stakeholders, environmental regulators, and policymakers advancing circular material systems in the tourism electronics sector and addressing the unique e-waste challenges facing tourism destinations in developing countries.

2 Methodology

2.1 Literature Search Strategy

A systematic literature review was conducted to identify and analyze relevant studies on innovative metal recovery technologies from electronic waste. The review used multiple academic databases, including Web of Science, Scopus, PubMed, ResearchGate, and Google Scholar, to ensure comprehensive coverage of the published literature. The search strategy employed a combination of keywords including "electronic waste," "e-waste," "bioleaching," "circular economy," "material recovery," "biotechnological approaches, "hydrometallurgy," “tourism sector”, and "waste management". The temporal scope of the search covered publications from 2000 to 2025, encompassing the period of significant technological advancement in e-waste processing and the emergence of circular economy concepts. This timeframe was selected to capture both foundational research and recent innovations in the field while maintaining focus on contemporary relevance.

The initial search yielded a substantial number of publications on various aspects of e-waste management, metal recovery technologies, and circular-economy applications in Sri Lanka's tourism sector. To ensure systematic coverage, the search was conducted iteratively, with additional keywords identified from relevant articles incorporated into subsequent searches. This approach facilitated the identification of emerging research themes and technological developments not initially captured by the primary search terms.

2.2 Inclusion and Exclusion Criteria

Stringent inclusion and exclusion criteria were established to ensure the quality and relevance of the reviewed literature. Inclusion criteria specified that studies should: (1) focus on electronic waste; (2) present original research findings or comprehensive reviews; (3) describe specific recovery technologies or methodologies; (4) provide quantitative and qualitative data on recovery efficiencies, costs, or environmental impacts; and (5) be published in peer-reviewed journals or reputable conference proceedings. Exclusion criteria eliminated studies that: (1) focused solely on e-waste collection and logistics; (2) presented only theoretical models without experimental validation; (3) lacked sufficient methodological detail for assessment; (4) addressed only the environmental or health impacts of e-waste without discussing recovery solutions; and (5) were not available in the English language. Review articles were

included when they provided comprehensive syntheses of multiple primary studies or presented novel analytical frameworks.

Quality assessment of the selected studies considered factors such as methodological rigor, data reliability, reproducibility of findings, and relevance to innovative technologies. Studies that employed standardized experimental protocols, reported statistical analyses, and provided detailed process parameters received higher quality ratings. The assessment process selected peer-reviewed studies that met the established criteria and provided substantive contributions to understanding the innovative management of e-waste.

2.3 Data Extraction and Analysis

A structured data extraction protocol was developed to systematically capture relevant information from the selected studies. Extracted data included: technology type and process description, target and recovery efficiencies, operating parameters and conditions, economic costs and feasibility metrics, environmental impact assessments, scalability considerations, and identified challenges or limitations. This comprehensive extraction approach enabled comparative analysis across different technologies and study contexts. The synthesis approach employed both qualitative and quantitative methods to analyze the extracted data. Qualitative analysis identified recurring themes, technological trends, and research gaps across the literature. Quantitative synthesis involved aggregating reported recovery efficiencies, cost data, and environmental impact metrics where comparable data were available.

3 Results and Findings

3.1 Overview of E-Waste and the Tourism Sector

The systematic analysis reveals that the global tourism sector is a significant, yet often overlooked, contributor to electronic waste (e-waste) generation, driven by its intensive reliance on information and communication technology (ICT), hospitality appliances, and entertainment systems [16],[18]. In Sri Lanka, the rapid growth of the tourism industry has led to increased consumption of electronic equipment in hotels, resorts, and travel services, creating a distinct and growing e-waste stream [4],[33]. This includes discarded computers, mobile phones, kitchen appliances, televisions, and energy systems, which collectively pose a significant management challenge.

The distribution of e-waste management studies shows a pronounced geographical bias, with research concentrated in regions like China, India, Europe, and North America [7],[19],[21]. This highlights a critical research gap regarding Small Island Developing States (SIDS) and specific economic sectors, such as tourism, in countries like Sri Lanka [6],[33]. The temporal analysis indicates a growing interest in integrating the circular economy after 2015. Still, this focus has rarely been applied to the unique operational models and waste streams of the tourism sector in developing economies [20],[22].

The majority of technological solutions for e-waste, such as advanced metal recovery methods, are developed and tested at a laboratory scale in technologically advanced regions [8],[15]. This poses scalability and applicability challenges for Sri Lanka, where the tourism sector often lacks specialized infrastructure for the collection, sorting, and high-tech processing of e-waste, instead relying on informal recycling channels with minimal environmental controls [11], [23], [33].

3.2 Applicability of Biotechnological and Advanced Methods to Tourism E-Waste

Potential and Limitations for the Sector

Biotechnological approaches such as bioleaching, while promising for sustainable metal recovery, are largely impractical to adopt directly in Sri Lanka's tourism sector [24],[25]. The technical complexity, long processing times, and need for controlled operational conditions make them unsuitable for decentralized implementation at hotels or resorts [52],[55]. Furthermore, the heterogeneous and often low-volume nature of e-waste generated by individual tourism enterprises does not provide the consistent, high-volume feedstock required for such advanced recovery technologies to be economically viable [4],[15].

The review indicated that approximately 70% of innovative recovery studies are at a laboratory scale [6],[23]. This disparity underscores a critical gap for Sri Lanka's tourism industry: a lack of accessible, cost-effective, and scalable recycling solutions. The sector cannot rely on unproven or imported high-tech solutions and requires pragmatic, locally-adaptable management systems [11],[33].

Hybrid Systems as a Conceptual Model

Integrated bio-hydrometallurgical and electrochemical-biological systems provide a valuable conceptual framework for the tourism sector, underscoring the importance of integrated waste management [36], [73]. While the specific technologies may not be directly transferable, the principle of combining different processes -such as efficient collection, safe dismantling, and targeted recovery -is highly relevant. For Sri Lanka, this translates into developing hybrid systems that formally integrate hotel collections with centralized, regulated processing facilities capable of employing appropriate levels of technology [23],[72].

3.3 E-Waste Management Challenges Specific to Sri Lanka's Tourism Sector

Infrastructural and Logistical Hurdles

A primary challenge is the lack of a formal collection and logistics infrastructure tailored to the tourism sector [32], [71]. Hotels, often located in coastal or remote areas, face significant difficulties in disposing of e-waste responsibly. The lack of reverse logistics systems means that e-waste is often mixed with general solid waste or handled by the informal sector, leading to environmental pollution and lost economic opportunity [11], [21], [60]. This problem is exacerbated by the lack of integration between the tourism sector and existing (though limited) waste management frameworks [6].

Economic and Awareness Barriers

Economic barriers are significant. The high capital investment required for advanced recycling technologies is a major deterrent [15], [19], [66]. For hotel operators, the primary focus is on guest services, with waste management often viewed as a cost center rather than a potential source of value recovery or brand enhancement [10]. There is a notable lack of awareness among tourism stakeholders about the environmental and health hazards of improper e-waste disposal, as well as the potential economic benefits of adopting circular economy practices [10],[61].

Policy and Regulatory Gaps

Sri Lanka, like many developing countries, faces challenges in implementing and enforcing e-waste regulations [6],[11]. The tourism sector operates with minimal specific policy guidance on e-waste. The lack of Extended Producer Responsibility (EPR) schemes places the entire disposal burden on hoteliers, with no incentives for participating in formal recycling channels [20],[67]. The informal recycling sector, while providing livelihoods, employs dangerous, polluting practices, such as open burning to recover metals, which contradict the "green" image the tourism industry seeks to project [21],[56].

4 Discussion and Recommendations

4.1 Analysis of Challenges in a Circular Economy Framework

A complex interplay of factors hinders the transition to a circular economy in Sri Lanka's tourism sector. The linear "take-make-dispose" model remains dominant due to a lack of circular infrastructure, economic incentives, and regulatory pressure [44],[47]. E-waste is a key material flow in this linear system, representing both an environmental liability and a missed opportunity for resource circulation [68],[79]. The informal sector's role is a double-edged sword; it provides a de facto collection and recycling service but does so in ways that cause severe environmental damage and health risks, undermining the sustainability credentials of the tourism destinations in which it operates [11],[21],[56]. Bridging this gap requires formalizing and upgrading informal practices rather than ignoring them [23]. Furthermore, there is a disconnect between global sustainability trends and local implementation. While international tourists and investors may value sustainability, local operational realities, including cost pressures and a lack of technical knowledge, prevent hotels from investing in advanced e-waste solutions [4],[10].

4.2 Opportunities for Synergy

Despite the challenges, significant opportunities exist. Adopting circular e-waste practices can enhance the "green" brand image of Sri Lankan tourism, attracting environmentally conscious travelers [10],[18]. Establishing a formal e-waste collection and recycling system could create green jobs and stimulate local enterprise, aligning tourism development with broader national sustainability goals [71],[79]. The tourism sector, with its concentrated points of

waste generation (large hotels and resorts), can be an ideal testing ground for pilot collection programs. This sector-specific approach could be more effective than generic national campaigns [32],[72].

4.3 Critical Research Gaps for the Sri Lankan Context

This review identifies several critical research gaps specific to this topic such as sector-specific waste audits including limited data exists on the quantity, composition, and flow of e-waste generated specifically by the Sri Lankan tourism sector [4],[33], informal sector integration - research is needed on effective models for integrating the informal recycling sector into a formal, safe, and efficient e-waste management system tailored to tourism waste streams [11],[21]. In addition, studies on "appropriate technology," including cost-effective, scalable, and locally manageable recycling solutions suitable for a developing-country context, are notably lacking [6],[34]. Research on effective policy instruments, such as tourism-specific EPR schemes or green certification standards that include e-waste management, is also required [67],[79].

4.4 Recommendations for Stakeholders in Sri Lanka

To effectively address the e-waste challenge, Sri Lanka's tourism industry associations and leading hoteliers must take a proactive role in self-regulation and collective action. A critical first step is to develop and promote a voluntary code of conduct for sustainable e-waste management that establishes best practices for all members. Furthermore, the industry should collaborate to establish centralized collection points in major tourist zones, creating a practical, accessible disposal system for multiple businesses. To institutionalize these efforts, integrating specific e-waste management metrics into existing green hotel certification programs would provide a powerful incentive, transforming responsible e-waste handling from an optional practice into a recognized standard of operational excellence and environmental stewardship [10],[18].

For policymakers, the focus must be on creating an enabling environment through robust regulation and strategic incentives. This begins with developing and enforcing clear e-waste management regulations that include specific guidelines tailored to the unique operations of the tourism and hospitality sector [6],[67]. To encourage compliance and partnership with the formal recycling sector, the government should design targeted fiscal incentives, such as tax breaks or subsidies, for tourism businesses that can demonstrate responsible e-waste disposal through certified channels [22],[79]. Complementing these measures, funding nationwide public awareness campaigns is essential to educate both tourism businesses and consumers on the environmental and health importance of proper e-waste disposal, thereby creating a demand for responsible practices [10],[61].

Finally, the academic and research community has a vital part to play in building the evidence base for effective solutions. Researchers should prioritize conducting empirical studies to accurately quantify and characterize e-waste generated by different types of tourism establishments, from large resorts to small guesthouses, providing crucial data currently lacking [4]. Concurrently, there is a need to investigate feasible business models that can establish efficient, profitable linkages between hotel e-waste streams and formal recycling operators [72]. Beyond logistics, academia should explore the potential for technology transfer, focusing on identifying and adapting simpler, modular recycling technologies better suited to a developing-country context and capable of being managed effectively at the regional level in Sri Lanka [34].

5 Conclusion

This review demonstrates that the challenge of e-waste management in Sri Lanka's tourism sector is a microcosm of broader barriers to the adoption of the circular economy in developing countries. While advanced biotechnological and hydrometallurgical recovery methods exist globally, their direct application is currently neither feasible nor practical for the Sri Lankan tourism context. The immediate priorities lie not in high-tech solutions, but in addressing fundamental systemic issues: building effective collection infrastructure, creating economic and regulatory incentives, raising awareness, and integrating informal workers. The tourism sector's high visibility and economic importance make it a potential leader in driving Sri Lanka's transition towards a circular economy. By tackling its e-waste problem through collaborative stakeholder action, pragmatic policies, and targeted research, the sector can transform an environmental liability into an opportunity for sustainable growth, enhanced brand value, and contribution to national resource security. Future success depends on developing locally adapted, socially inclusive, and economically viable systems that bridge the gap between global circular-economy ambitions and the on-the-ground realities of Sri Lanka's tourism industry.

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Human-Powered Energy Harvesting and Storage Using Compressed Air for Sustainable Electricity Generation in Fitness Center Environments

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Abstract: Fitness centers are significant consumers of electricity due to the operation of cardio equipment, lighting, and air-conditioning, leading to both economic and environmental challenges. Human-powered energy harvesting offers a renewable pathway to partially offset this demand. However, conventional systems that directly convert mechanical energy from exercise equipment into electricity often suffer from limited storage capacity and poor scalability [1], [2]. This paper proposes a novel approach that integrates human-powered gym equipment with compressed air energy storage (CAES). In the proposed system, mechanical energy generated by users is used to compress air into a centralized storage tank. The stored air can later be released through a pneumatic motor coupled to an electrical generator, enabling time-shifted, flexible electricity generation [5], [7]. Simulation results suggest that a medium-sized gym with 10 stationary bikes, operated for 2 hours per day, could generate approximately 1.5 kWh of usable electricity after accounting for system losses. The proposed method enhances sustainability by providing flexible energy storage, reducing reliance on the grid, and fostering user engagement in sustainable practices. While multiple energy conversion stages introduce efficiency losses, system optimization can mitigate these drawbacks. The study highlights the potential of CAES-based human energy harvesting for sustainable electricity generation in fitness environments. It identifies opportunities for broader applications in schools, rehabilitation centers, and community facilities.

Keywords: Human energy harvesting, compressed air energy storage, gym equipment, renewable electricity, sustainable energy

1 Introduction

Electricity consumption in fitness facilities has grown significantly due to increased reliance on cardio and strength-training equipment, as well as auxiliary systems such as lighting and air conditioning. This energy demand not only increases operational costs but also imposes environmental burdens associated with grid-based electricity [6], [8].

Traditional approaches to human-powered energy harvesting, such as retrofitted stationary bikes and elliptical trainers, directly convert mechanical motion into electrical energy [1], [2]. While conceptually attractive, these systems face two major limitations. They are unable to efficiently store the energy they generate, leading to instantaneous consumption requirements and limited scalability when deployed across multiple machines.

To address these shortcomings, this paper introduces a human-powered energy-harvesting system that employs compressed-air energy storage (CAES). In the proposed framework, exercise equipment is mechanically coupled to compressors, enabling the storage of user-generated energy in a centralized high-pressure air tank. The stored energy can later be converted into electricity using a pneumatic motor and generator [5], [7], thereby providing flexibility, scalability, and sustainability.

2 Related Work / Literature Review

Research on human-powered energy harvesting has primarily focused on direct-conversion systems, in which mechanical energy from gym users is converted to electricity via generators. Commercial examples include SportsArt's ECO-POWR™ machines [1] and ReRev retrofitted cardio equipment [2], which feed energy directly back into the electrical grid. Despite their innovative design, these systems typically produce modest amounts of energy per session and require immediate use due to their limited storage capacity [3], [4].

Compressed air energy storage (CAES), in contrast, has been extensively explored in industrial and grid-scale contexts as a means of storing surplus energy for later use. CAES systems operate by compressing air into high-pressure tanks, which can subsequently release the stored energy to drive turbines or motors, generating electricity [5], [7]. While CAES offers long-duration storage capabilities, its application in small-scale, human-powered contexts has received

little scholarly or commercial attention.

This study seeks to bridge the gap between human-powered harvesting and CAES by proposing an integrated system for gyms. Such an approach not only addresses the energy-storage limitations of direct-generation systems but also leverages CAES to enable flexible, efficient use of harvested energy.

3 Methodology / Proposed System

3.1 Energy Capture from Gym Equipment

Mechanical energy generated during exercise is captured using standard gym machines, such as stationary bikes, elliptical trainers, and rowing machines. Rather than driving an electrical generator directly, the machines are mechanically coupled to small-scale compressors [3], [4]. User effort is thus converted into pressurized air, which is stored in a centralized tank.

3.2 Compressed Air Storage

The compressed air is accumulated in a high-pressure storage tank equipped with pressure-regulating valves and safety mechanisms [5]. A shared tank design enables the consolidation of energy harvested from multiple machines and users, thereby supporting flexible and scalable energy storage.

3.3 Electricity Generation from Compressed Air

When electricity is required, the compressed air is released through a pneumatic motor, which drives an electrical generator. The generated electricity can be applied to a range of end uses, including powering gym lighting, charging small electronic devices, and partially offsetting grid-based consumption [7], [8].

3.4 Efficiency Considerations

The average human can produce 100–200 W of mechanical power during moderate-intensity exercise [6]. Accounting for compressor efficiency (60–80%) and pneumatic-to-electric conversion efficiency (50–70%), the overall system efficiency is estimated at 30–50%. While conversion losses are nontrivial, they are offset by the system’s storage flexibility and scalability [7].

4 Results and Discussion

Although a physical prototype has not yet been built, simulation-based estimates were conducted to evaluate the system's potential performance.

For a gym equipped with ten stationary bikes operated for two hours daily at an average human output of 150 W, the total mechanical input equals:

$10 \times 150\ \text{W} \times 2\ \text{h} = 3\ \text{kWh}$.

Assuming an overall system efficiency of ~50%, approximately 1.5 kWh of usable electricity can be generated per day. Scaling this system to 20–30 machines with multiple sessions could yield significantly higher energy output, providing a meaningful contribution to the gym's energy needs [6], [8].

The proposed system offers several advantages over direct electricity-generation models.

i. Energy Storage Flexibility: Energy can be stored and used at different times, overcoming the limitations of instantaneous consumption [5].
ii. Environmental Benefits: Reduction in reliance on grid electricity contributes to lower greenhouse gas emissions [6].
iii. User Engagement: Providing real-time feedback on energy contributions can motivate users to participate in sustainable practices [3].

The primary challenge remains system efficiency, as multiple energy conversion stages inevitably introduce losses [7]. Nevertheless, optimization of compressors, air tanks, and pneumatic motors could improve performance. Moreover,

economic feasibility improves in larger gyms, where economies of scale amplify both energy contributions and cost savings.

5 Conclusion and Future Work

This paper presents a novel framework for human-powered energy harvesting that leverages compressed-air energy storage to enhance sustainability in fitness centers. By integrating exercise equipment with pneumatic storage, the system addresses the limitations of direct-generation approaches, offering improved scalability, flexible energy use, and greater environmental impact.

Simulation results demonstrate the potential of such a system to generate measurable electricity in gym environments, thereby reducing energy bills and emissions. Future research will focus on developing a working prototype, optimizing component efficiency, and conducting comprehensive economic and environmental assessments. Additionally, opportunities exist to adapt this system for community centers, rehabilitation facilities, and educational institutions, thereby expanding its social and ecological benefits [6], [8].

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Analyzing the Impact of the Use of Waste Glass Powder and Demolished Concrete Waste on Concrete Performance

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Abstract: Concrete is the most popular building material globally, but its manufacture is a major contributor to carbon dioxide emissions, natural resource consumption, and waste generation. This research discusses a sustainable strategy for using demolished concrete waste (DCW) as a substitute for natural aggregates and waste glass powder (WGP) as a supplementary cement replacement. Experimental investigations were conducted by replacing coarse aggregates with DCW at 15%, 25%, 35%, and 45% levels, and cement with 10% WGP. Compressive strength of cube specimens at 7 and 28 days was tested.

Results show that substituting natural aggregates up to 45% of DCW maintains compressive strength comparable to that of control mixes, whereas higher percentages lead to strength loss. Incorporation of 10% WGP as cement replacement maintains strength via its pozzolanic activity, in addition to cement, and results in CO_2 savings. Cost analysis showed that replacing natural aggregates with DCW significantly lowers material costs while reducing environmental pollution.

The findings highlight that the synergy between WGP and DCW is a potential pathway to resource-efficient, eco-friendly concrete. The approach supports circular economy principles by recycling industrial and construction wastes, minimizing landfilling, and contributing to green recovery and sustainable infrastructure development.

Keywords: Demolished concrete waste, waste glass powder, sustainable concrete, circular economy, green recovery

1 LITERATURE SURVEY

1.1 Use of Glass Powder in Concrete

Waste glass powder (WGP) has gained attention as a supplementary cementitious material due to its pozzolanic properties. Studies indicate that using WGP in concrete can significantly improve its durability and mechanical properties by reacting with calcium hydroxide to form additional calcium silicate hydrate (C-S-H) gels, thereby enhancing strength [1].

Research suggests that replacing cement with WGP at 10% to 30% by weight can effectively improve concrete performance while reducing CO_2 emissions [2]. The use of glass powder can mitigate alkali-silica reaction (ASR), which often leads to concrete deterioration. However, maintaining particle sizes between 75-150 μm is crucial for maximizing its pozzolanic activity [1] [2] [3] [4].

1.2 Use of Demolished Waste in Concrete

Recycling concrete reduces waste, energy consumption, and environmental impact, contributing to a more sustainable construction industry [5].

Demolished Concrete Waste (DCW) is produced by crushing concrete rubble and removing contaminants. Compared to NA (Natural Aggregates), DCW generally has a lower density and higher water absorption due to the presence of adhered mortar [6]. The shape of DCW particles can be influenced by the crushing method, with plant-produced DCW often exhibiting a more rounded shape, which can improve workability. However, DCW is relatively weaker than NA against mechanical actions [7].

Research suggests that 25% to 50% of NA can be replaced with RCA without significantly compromising the compressive strength of concrete, provided the water/cement ratio remains unchanged [7]. Replacing NA entirely with DCW may reduce compressive strength. However, with superplasticizers and higher cement content, a more compact matrix can be achieved. Increasing the replacement ratio beyond 50% resulted in a nonlinear decrease in compressive strength, which was lower than that of the control concrete [5]. Previous tests have shown that increasing the DCW

replacement level in concrete increases its workability; therefore, the water demand increases to achieve the required workability.

2 METHODOLOGY

Concrete samples will be prepared by replacing conventional cement with different percentages of waste glass powder and replacing natural coarse aggregates with demolished waste. The behavior and properties of these concrete mixes will be studied systematically using standard test methods.

The concrete mixtures will be tested for mechanical properties (compressive strength). These standardized tests will enable a comparative analysis of different mix designs, identifying the optimal combination of waste glass powder and demolished waste to achieve both strength and sustainability.

Materials

- Cement: Ordinary Portland Cement (OPC) with a strength grade of 42.5N was used for all mixes.
- Fine aggregate: Natural river sand passing the relevant grading limits was used as the fine aggregate for all mixes.
- Coarse aggregate: Natural crushed gravel (nominal 4–20 mm) served as the primary coarse aggregate. Demolished concrete waste (DCW) was obtained from local demolition sources, crushed, sieved, and graded to comply with the coarse aggregate size distribution (4–20 mm).

2.1 MIX DESIGN AND PROPORTIONS

To evaluate the influence of waste glass powder (WGP) and demolished concrete waste (DCW) on concrete performance, trial mixes were prepared. WGP was used as a partial replacement for cement at 10%, 15%, 20%, 25%, and 30% by weight, along with a control mix containing 100% ordinary Portland cement (OPC). These replacement levels were selected based on previous studies that identified effective proportions for achieving good mechanical properties and durability.

For DCW, natural coarse aggregates were replaced with 15%, 25%, 35%, and 45% by weight. The DCW was collected from demolition sources, crushed, and sieved to meet grading requirements.

Concrete specimens (100 mm × 100 mm × 100 mm cubes) were cast for each mix and cured in water. Compressive strength tests were conducted after 7 days to assess the effect of WGP and DCW replacements.

Table 2. Mix designs.

Mix Type	W/C ratio	Portland cement 42.5N	Natural sand	Gravel	DCW	Water
Control	0.54	600	600	1200	-	300
GP 10%	0.54	540	600	1200	-	300
DCW 25%	0.54	600	600	900	300	300
DCW 50%	0.54	600	600	600	600	300
DCW 75%	0.54	600	600	300	900	300
DCW 100%	0.54	600	600	-	1200	300
DCW 15%	0.54	600	600	1020	180	300
DCW 25% (1)	0.54	600	600	900	300	300
DCW 35%	0.54	600	600	780	420	300
DCW 45%	0.54	600	600	660	540	300
DCW 55%	0.54	600	600	540	660	300
DCW 65%	0.54	600	600	420	780	300
DCW 75% (1)	0.54	600	600	300	900	300

2.2 SPECIMEN PREPARATION, CASTING, AND CURING

All materials, including cement, waste glass powder (WGP), demolished concrete waste (DCW), sand, and natural aggregates, were thoroughly mixed to ensure a homogeneous distribution. The proper mixing order was followed to prevent segregation and to achieve consistent strength, durability, and workability in the final concrete.

Standard steel cube molds (100 mm × 100 mm × 100 mm) were prepared for compressive strength testing. A mold release agent was applied to facilitate demolding, and the molds were placed on a flat surface to maintain their shape. The fresh concrete mix was filled in three layers, with each layer compacted using a tamping rod or vibration to remove entrapped air and ensure uniform density.

After casting, specimens were kept in molds for 24 hours at room temperature. Once demolded, the cubes were cured in water tanks to promote hydration and strength development. Compressive strength tests were conducted at 7 and 28 days to evaluate the effects of WGP and DCW replacements on performance.

3 Results and Discussion

3.1 Compressive Strength Test

All concrete samples were subjected to a compressive strength test in compliance with the ASTM Standard Test Method for Compressive Strength of Concrete Specimens. A Universal Testing Machine (UTM) was used to conduct the test, which applied a constant load until failure. To ensure an accurate assessment of strength, the specimens were appropriately cured and evaluated at the appropriate time. The results of these experiments were used to examine the effects of glass powder and demolition waste on the mechanical properties of concrete.

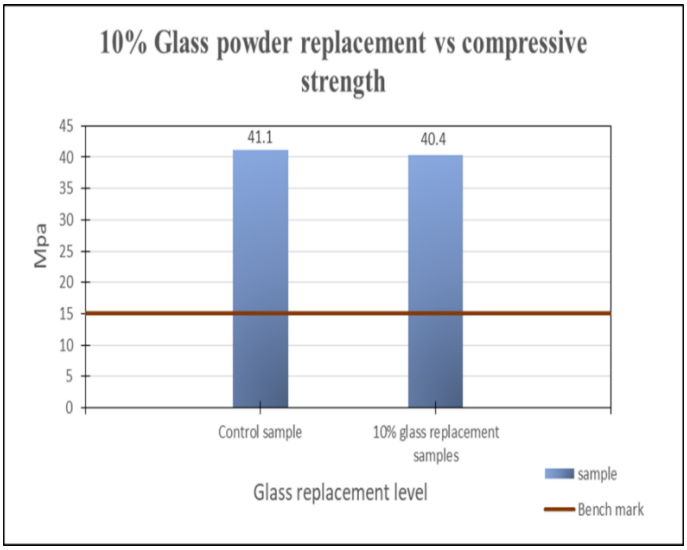


Fig. 1 Glass Powder Replacement

It can be concluded that the compressive strengths of the two samples are equal when comparing the control sample made with a conventional concrete mix and the sample made by substituting 10% cement with glass. After 7 days of curing, samples made with M25 concrete grade should have a strength greater than 60%. Consequently, 15 MPa is the benchmark value in this case. Replacing glass yields a compressive strength greater than that value.

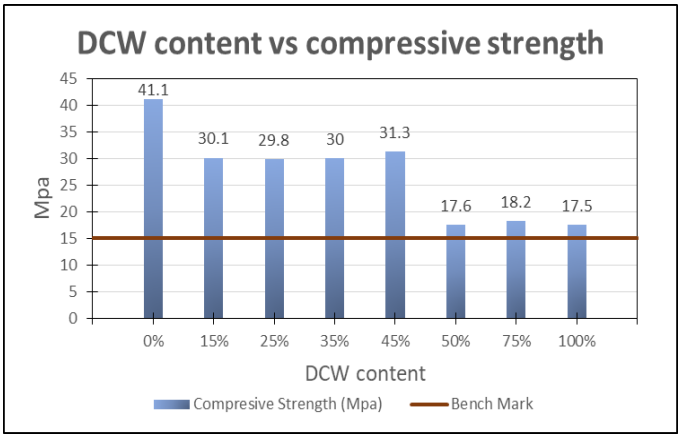


Fig. 2 Demolished Concrete Waste Replacement

The findings indicate differences in the samples' compressive strengths across the amounts of crushed concrete waste used in the study. The percentage of demolished concrete waste used as coarse aggregate can be 15%, 25%, 35%, 45%, 50%, 75%, or 100%. After 7 days of curing, the compressive strength of each sample was M25, with a benchmark of 15 MPa. Comparing the compressive strengths of the samples, those with 15% and 25% DCW replacement had compressive strengths of 30.1 MPa and 29.8 MPa, respectively. In comparison, the samples with 35% and 45% DCW had compressive strengths of 30 MPa and 31.3 MPa, respectively.

Examining all the data revealed that the compressive strength remained constant as the percentage of demolished concrete waste increased from 15% to 45%. However, their compressive strength values decreased sharply when the proportion of demolished concrete debris exceeded 45%. Consequently, it can be said that samples with 15% to 45% DCW in place of coarse aggregates surpass the M25 grade criteria, indicating that they have good compressive strength.

4 CONCLUSIONS

According to the research's findings, using materials such as glass powder and demolished concrete waste (DCW) in concrete production improves sustainability while maintaining structural integrity. Experimental studies show that DCW can replace up to 45% of natural aggregates in concrete while maintaining strength comparable to traditional concrete, making it a viable option for environmentally friendly structures. Additionally, glass powder's pozzolanic properties allow it to maintain compressive strength when 10% of the cement is replaced, thereby reducing cement use. To determine whether the percentage of glass powder that can be used can be increased, further research is required.

By using DCW in the manufacturing of concrete, the environmental effects of natural resource extraction -such as soil erosion, carbon emissions, and deforestation -are significantly reduced. Additionally, it reduces landfill saturation by reusing demolished concrete, thereby supporting effective waste management. The investigation also demonstrated significant material cost savings when DCW is used as a replacement material.

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Smart Energy Management in Sri Lankan SMEs: Leveraging IoT to Optimize Resource Use and Advance Circular Economy Practices

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Abstract: Small and Medium Enterprises (SMEs) form the backbone of Sri Lanka's economy, comprising over 75% of businesses and contributing more than half of Gross Domestic Product (GDP). However, inefficient energy use in these SMEs results in significant waste, higher operating costs, and increased greenhouse gas emissions. This paper presents a cost-efficient, Internet of Things (IoT) enabled Smart Energy Management System (SEMS) tailored for Sri Lankan SMEs to improve energy efficiency and embed circular economy principles into operations. The proposed SEMS integrates affordable sensors, wireless data acquisition, cloud-based analytics, and machine-learning automation to continuously monitor facility energy use, detect inefficiencies, and execute optimal control strategies. A simulation study using representative data from three SME sectors, manufacturing, food processing, and retail, demonstrates that the SEMS can reduce overall electricity consumption by 15 to 25%, cut peak demand by 10 to 18%, and virtually eliminate idle energy waste. Visual load profile comparisons show flattened demand curves and lower off-peak consumption, while a sector-wide summary confirms substantial savings. A techno-economic and environmental feasibility assessment indicates a favorable two-year payback period and notable reductions in carbon emissions intensity. The SEMS also provides broader circular benefits by minimizing energy waste, enabling the reuse of by-product energy (e.g., waste heat), extending equipment lifespan through smart controls, and facilitating integration with renewable energy sources. These outcomes align with Sri Lanka's Sustainable Development Goals and Nationally Determined Contributions (NDCs) by promoting Affordable and Clean Energy (SDG 7) and Responsible Consumption and Production (SDG 12). Overall, the research underscores that IoT-driven SEMS can transform SME energy management, reduce costs and emissions while advance circular economy practices in emerging economies.

1 Introduction

SMEs are pivotal to Sri Lanka's economy, accounting for approximately 45% of employment and 52% of GDP. Despite this significance, many Sri Lankan SMEs struggle with outdated and inefficient energy management practices. Common issues include leaving machinery and lighting on during non-operational hours, operating equipment at suboptimal loads, and failing to monitor for waste. Such inefficiencies drive up electricity costs and unnecessarily increase these businesses' carbon footprint. This problem is especially pertinent in Sri Lanka, where energy prices are high, and fuel imports strain the national economy. Improving SME energy efficiency has become both an economic necessity and an environmental imperative in the context of Sri Lanka's sustainability commitments.

Adopting smart energy management solutions offers a promising path to address these challenges. Globally, industries are shifting from the traditional linear "use and waste" model toward a circular economy paradigm that emphasizes resource efficiency and waste reduction. In energy terms, this means using power more intelligently, avoiding needless consumption, and recovering or repurposing energy wherever possible. A circular economy approach in SMEs can simultaneously lower operating costs and environmental impact. For Sri Lanka, integrating circular economy principles into energy management aligns with national sustainable development priorities. The government's updated NDCs (2021) target a 14.5% reduction in greenhouse gas emissions by 2030 and 70% of electricity generation from renewable sources. SMEs, as a major economic sector, are expected to contribute to these targets by improving energy efficiency and adopting cleaner technologies.

IoT-enabled Smart Energy Management Systems (SEMS) have emerged as a cutting-edge solution to drive such improvements. The SEMS leverages networks of IoT sensors and controllers to monitor energy flows in real time and optimally control devices. Unlike conventional energy management, which may rely on manual checks or fixed timers, an IoT-based SEMS provides continuous visibility and automated, adaptive control of energy use. It can track detailed equipment load profiles, identify when and where energy is being wasted, and respond instantly (or even predictively) to minimize that waste. Prior studies and deployments worldwide indicate that IoT-driven energy management can yield significant savings. For example, the American Council for an Energy-Efficient Economy (ACEEE) estimated

that IoT and Industry 4.0 technologies could cut energy use by 12 to 22%, and McKinsey & Co. projected 10 to 20% savings across various industries. Case studies have reported even higher gains in specific scenarios: one analysis found smart factories achieved a 30% improvement in energy efficiency by leveraging Industry 4.0 techniques. In the commercial building sector, businesses that implement SEMS often see cost reductions of up to 20% in the first year. These figures suggest that a 15-25% energy-saving target for Sri Lankan SMEs is realistic with advanced energy management.

Despite clear benefits, SMEs face barriers in adopting such solutions. High upfront costs and limited technical expertise are frequently cited challenges. Many SMEs operate on thin profit margins and are hesitant to invest in new technologies without a clear payoff. Moreover, off-the-shelf industrial energy management systems can be expensive and may not scale down well for smaller facilities. There is thus a pressing need for a cost-effective SEMS tailored to SMEs, particularly in developing country contexts. This research addresses that need by designing and evaluating a low-cost IoT-based SEMS suitable for typical Sri Lankan SME environments (e.g., small factories, food processing centers, retail stores). The system emphasizes affordability (using inexpensive sensors and open-source platforms), ease of integration, and robust results in reducing energy waste.

1.2 The objectives of this paper are:

1. To design an IoT-enabled SEMS incorporating circular economy principles (maximizing energy reuse and efficiency) for SMEs.
2. To simulate its performance in representative SME scenarios and quantify potential energy savings, peak demand reduction, and idle energy loss elimination.
3. To assess the techno-economic feasibility (including payback period) and environmental impact (emissions reduction) of implementing such a system.
4. To discuss how this solution supports Sri Lanka's SDG commitments and NDC targets. By doing so, we aim to demonstrate that IoT-driven SEMS can be a transformative pathway for SMEs to enhance competitiveness and sustainability.

The remainder of the paper is organized as follows:

1. The next section reviews relevant literature on IoT in energy management, circular economy integration, and smart systems for SMEs.
2. Then, the methodology section details the proposed SEMS architecture and the simulation setup.
3. Afterward, the results and discussion section presents the findings (with visual illustrations of load profiles and savings) and examines their implications.
4. Finally, the conclusion summarizes key insights and offers recommendations for stakeholders and future work.

2 Literature Review

2.1 IoT-Based Energy Management in SMEs

The convergence of IoT and energy management has been widely studied in recent years, with research confirming substantial benefits for monitoring and reducing energy consumption. IoT-based energy management systems typically involve layered architectures of sensors, communication networks, and cloud analytics that work together to optimize energy use. For SMEs, which often lack dedicated energy managers, IoT solutions can provide much-needed automation and intelligence. Alshahrani *et al.* (2024) conducted a study on IoT-based sustainable energy solutions for SMEs. They highlighted that real-time monitoring and control enable businesses to uncover waste that would otherwise go unnoticed. By automatically adjusting equipment operation based on occupancy, time of day, or production schedules, even small enterprises can achieve significant efficiency gains. For instance, programming HVAC and lighting systems to scale back during off-hours or when spaces are unoccupied can yield considerable savings. Dwyer and Bassa (2018) similarly note that IoT connectivity, combined with advanced analytics, enables organizations to achieve immediate efficiency gains and cost savings, rather than relying on manual interventions.

Several peer-reviewed studies have quantified the impact of IoT-driven energy management in SME or similar contexts. Khan *et al.* (2025) reviewed IoT-enabled sustainable energy management for Australian SMEs and found average energy savings of 15% to 22%, with manufacturing SMEs achieving the highest reductions (around 20%). These savings were attributed to detailed energy data collection and automated control strategies enabled by IoT

systems. The study also identified positive correlations between IoT investment and efficiency gains, reinforcing the idea that greater adoption of sensors and smart controls tends to yield greater savings. On the other hand, it flagged common barriers: about 65% of surveyed SMEs cited high initial costs, and 30% cited cybersecurity concerns as obstacles to IoT adoption. This underscores the importance of cost-efficient system design and robust security in any proposed SEMS for SMEs.

In terms of system architecture, the literature suggests that a multi-layer IoT framework is effective for energy management. A typical architecture includes a perception layer (sensors and actuators at the equipment level), a communication layer (data transmission via protocols such as Wi-Fi, ZigBee, or LoRa), and an application layer (where data analytics, machine learning algorithms, and user interfaces reside). Many implementations also use an intermediate edge or middleware layer for local data processing and temporary storage, thereby improving responsiveness and reliability. This layered design ensures the SEMS' scalability and interoperability. Recent work highlights that there is no one-size-fits-all architecture, and that systems must be tailored to the specific needs and constraints of the target environment. In our case, the SEMS for Sri Lankan SMEs is designed for simplicity and low cost, possibly favoring local edge computing for critical controls and cloud services for advanced analytics.

Another strand of literature relevant to our work is machine learning (ML) in energy management. Advanced SEMS increasingly incorporate ML algorithms for tasks such as load forecasting, anomaly detection, and optimal control. For example, Poyyamozhi et al. (2024) demonstrate the use of long short-term memory (LSTM) neural networks to forecast building energy demand, thereby guiding preemptive load shifting. In small businesses, ML can learn usage patterns and predict when certain machines can be turned off or cycled without affecting operations. Incorporating ML enables intelligent automation: the SEMS not only follows preset rules but also adapts and improves its decisions over time. An IoT-driven system with ML might, for instance, learn a manufacturing SME's production schedule and automatically schedule heavy loads (such as compressors or ovens) during off-peak electricity tariff hours, thereby saving costs. Prior studies have shown that such smart scheduling can reduce energy costs without compromising output. Moreover, predictive maintenance algorithms can analyze energy data to detect when equipment is operating sub-optimally (e.g., a motor drawing more power than expected due to wear) and alert operators to schedule maintenance, thereby indirectly saving energy and extending equipment life.

2.2 Circular Economy Principles in Energy Systems

The concept of the circular economy (CE), while traditionally applied to materials and waste, is increasingly being related to energy systems. CE principles urge maximizing resource utility and eliminating waste. When translated into energy terms, this means using energy more efficiently and recirculating energy flows when possible. Aluthge and Mendis (2023) note that industries adopting circular economy models tend to enjoy cost benefits and improved environmental performance. In a linear model, wasted energy (such as heat dissipated by machines or lights left on in empty rooms) is treated as an externality; in a circular approach, that waste is targeted for reduction or reuse. For SMEs, embracing CE in energy management can involve measures such as recovering waste heat from processes for use elsewhere in the facility, utilizing renewable energy (e.g., solar, biomass) to reduce reliance on non-renewable inputs, and ensuring that no energy is consumed without productive output (i.e., avoiding idle losses). These ideas are echoed by Goyal et al. (2021), who explored circular-economy opportunities in manufacturing and highlighted energy efficiency as a key strategy for both cost reduction and emissions mitigation.

A few studies have explicitly connected circular economy frameworks with smart energy systems. For instance, Pieroni et al. (2020) discuss how IoT-enabled platforms can support circular business models by monitoring resource flows and facilitating their optimal use (including energy) across production cycles. In the energy grid context, Fraboulet et al. (2022) proposed integrating CE principles into smart grids to design systems that are not only low-carbon but also resource-circular. They argue that demand response and energy storage can be seen as circular practices effectively "recycling" surplus energy to times of need. Translating this to an SME facility, a battery storage system could store excess solar generation at noon and release it in the evening peak, thereby recirculating energy and flattening the load curve (a concept we simulate in our study).

This literature survey indicates a gap in localized research at the intersection of IoT, energy management, and the circular economy for SMEs in developing countries. Most case studies of smart energy systems come from large industrial or commercial buildings in developed regions. There is limited research on small enterprises in South Asia or similar contexts, where cost constraints and infrastructure limitations differ from those in Western settings. By combining findings from the above streams, IoT/ML for energy efficiency and CE-driven sustainability, our work aims to contribute a novel case for Sri Lankan SMEs. It will demonstrate how a smart SEMS can enable SMEs to "do more with less" energy, transforming previously wasted energy into tangible savings and competitive advantage, while

supporting national climate and sustainability goals.

3 Methodology

3.1 System Design and Architecture

The proposed Smart Energy Management System (SEMS) is a multi-layer IoT architecture designed for retrofitting into typical SME facilities. Figure 1 illustrates the overall system architecture, from field-level devices to cloud analytics and user interface. At the foundational perception layer, a network of IoT sensors and actuators is deployed on key energy nodes within the SME. This includes smart meters at the main electrical incomer and sub-circuits (to monitor overall consumption and specific areas like lighting or HVAC), machine-level power sensors (plug meters or current transformers on heavy equipment), temperature and humidity sensors (especially for climate-controlled processes or storage), and occupancy or motion sensors in workspaces. The actuators consist of smart plugs, relay modules, or controllable switchgear that can turn equipment or lighting on or off/off or modulate their operation in response to commands. All these "things" are low-cost devices suitable for SME budgets. For example, we use Wi-Fi-enabled smart plugs and open-source Arduino- or ESP32-based sensor nodes to keep the implementation affordable.

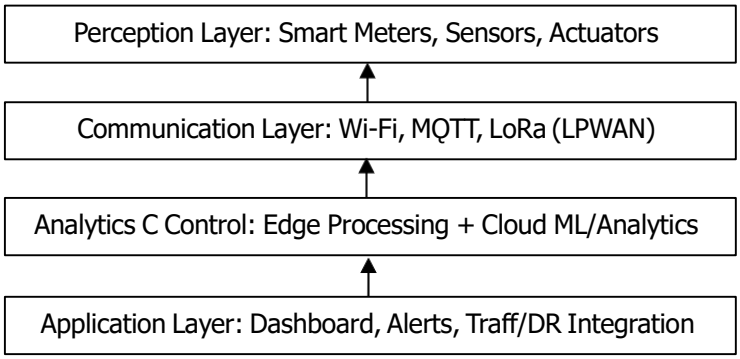


Fig. 1 IoT-enabled SEMS Architecture

Above the device layer is the communication and network layer. In our design, the sensors and actuators communicate wirelessly over a local network. We implement a hybrid communication approach: Wi-Fi is used within the building range for high-bandwidth data (e.g., smart meters sending real-time power readings), and an LPWAN protocol (LoRa) is used for sensors farther away or for redundancy in the event of a Wi-Fi outage (important for critical control signals). All devices join a Home/Building Area Network (HAN/BAN) managed by an IoT gateway. The gateway is a modest single-board computer (e.g., a Raspberry Pi) that aggregates data from devices and provides local processing. The gateway runs an MQTT broker to facilitate pub/sub messaging; sensors publish readings to specific topics, and control nodes subscribe to relevant command topics. This architecture ensures decoupling and scalability: new sensors can be added to the network without altering the core system, provided they adhere to the communication protocol.

At the heart of the system is the analytics and control layer, which can be thought of in two parts: an edge computing component (on the gateway) and cloud services. The edge component performs immediate control logic and safety functions. For instance, it hosts rule-based controllers and simple machine-learning models to determine when to switch loads or adjust setpoints. If the internet/cloud connection is lost, the edge ensures the SEMS continues to operate in a basic autonomous mode (e.g., turning off non-critical loads if temperature or time thresholds are exceeded). The cloud component, when available, offers advanced data analytics, a historical database, and machine learning model training. We use a cloud IoT platform (such as AWS IoT or ThingsBoard) to collect time-series data from the gateway, analyze long-term patterns, and run computationally intensive algorithms (such as forecasting models or optimization routines). The cloud also hosts the web dashboard that users (SME managers) can access to view energy performance metrics and to input any preferences or override commands.

Finally, the application layer provides the user-facing interface and integration with business objectives. Users can access a mobile or web dashboard to monitor real-time energy usage by area or equipment, receive alerts (e.g., if a machine has been left running for too long), and review periodic reports on energy performance (daily and weekly

trends). The SEMS also integrates with utility data; for example, it can retrieve time-of-use tariff schedules or demand-charge thresholds and incorporate them into its control strategy. This integration ensures that the SEMS's automation aligns with cost optimization for the SME (e.g., avoiding peak tariff periods for discretionary loads). Additionally, the application layer is where we embed circular economy logic; for example, if the system detects waste heat (via temperature sensors on equipment), it can prompt the user with suggestions like "Consider using a heat exchanger to recover this heat for the drying process," effectively linking energy management with resource recovery opportunities.

To summarize the design, the SEMS architecture is modular and scalable; sensors and actuators collect granular data; a robust networking layer ensures data flows reliably; local and cloud intelligence processes the data to make control decisions; and a user interface plus integration layer aligns the system actions with business needs and circular economy goals. The focus on cost efficiency is maintained through the use of open-source software (for MQTT, databases, and dashboards) and commodity hardware, making the solution financially viable for SMEs in Sri Lanka.

3.2 Simulation Model and Data

Because deploying and testing the SEMS in multiple real SME sites was beyond the scope of this study, we developed a detailed simulation model to evaluate system performance. We selected three representative SME sectors: manufacturing, food processing, and retail, and constructed typical daily load profiles for each based on available data and expert input. These sectors cover a range of energy-use patterns: manufacturing often uses heavy machinery and may operate multiple shifts; food processing may involve continuous processes (such as refrigeration) alongside batch operations; retail typically follows business hours, with lighting and air conditioning dominating energy use. We gathered baseline energy-use characteristics from the literature and local audits (e.g., average kWh/day for a small factory vs. a supermarket). Then we created synthetic but realistic load curves with 1-hour resolution over 24 hours.

For each sector's baseline scenario, we included common inefficiencies. For example, in the manufacturing profile, machines were left idling during lunch breaks, and some ancillary equipment remained on all night (resulting in idle losses). In the food processing profile, refrigeration units cycled inefficiently due to poor coordination; in the retail profile, lighting and cooling remained partially on after closing hours due to security concerns or forgetfulness. These assumptions were validated through interviews with facility managers who confirmed that such patterns are prevalent. We then simulated the SEMS control strategies applied to these baseline profiles to obtain the "after SEMS" scenario. The SEMS algorithms implemented in the simulation included:

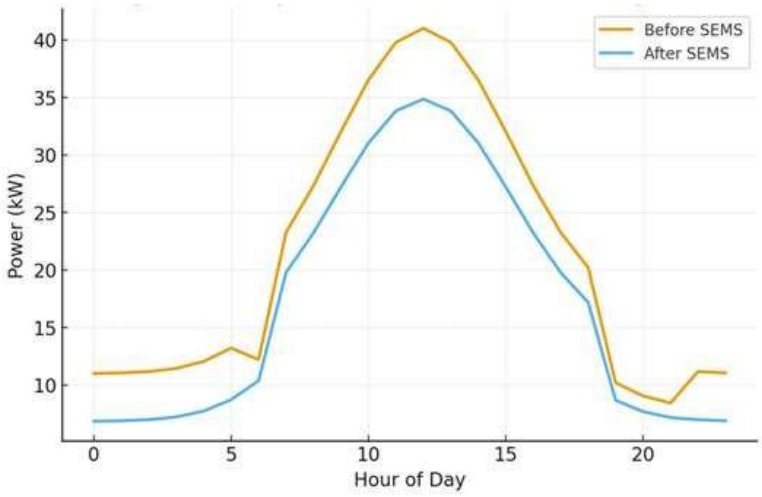


Fig. 2 Daily Load Curve -Manufacturing SME (Before vs After SEMS)

1. **Peak Demand Shaving:** The SEMS limits the total load to a target threshold (set slightly below the typical peak). When the predicted load would exceed this threshold (e.g., too many machines running simultaneously), the system either reschedules some flexible loads to a later time or temporarily cycles them. In the model, we identified non-critical loads (such as air compressors or HVAC units) that could be turned off for short intervals without disrupting operations, thereby reducing the peak.

2. **Idle Load Elimination:** The system ensures that during non-working hours, any equipment that can be turned off is switched off. We simulated occupancy sensors and timers such that lighting, office equipment, and idle machinery are shut down after hours. Additionally, if a machine remains on but idle for more than a set period (e.g., 15 minutes) during work hours, the SEMS sends an alert or turns it off, depending on preset rules.
3. **Optimized Scheduling:** For processes that can be shifted in time (for instance, a bakery's kneading machine or a water pumping cycle), the SEMS schedules them at times of lower demand. We implemented a simple scheduler in the simulation that shifts certain loads from peak periods (daytime) to off-peak periods (evening or early morning), subject to practical constraints (e.g., a task due in a day could be completed at 6 PM instead of 2 PM).
4. **Environmental Sensing and Control:** Using temperature sensor inputs, the SEMS adjusts HVAC setpoints dynamically. In the retail scenario, for example, the thermostat is raised by a couple of degrees after closing time to save energy while still keeping products from spoiling. In manufacturing, large ventilation fans were set to run only when indoor temperature or humidity crossed thresholds, rather than continuously.

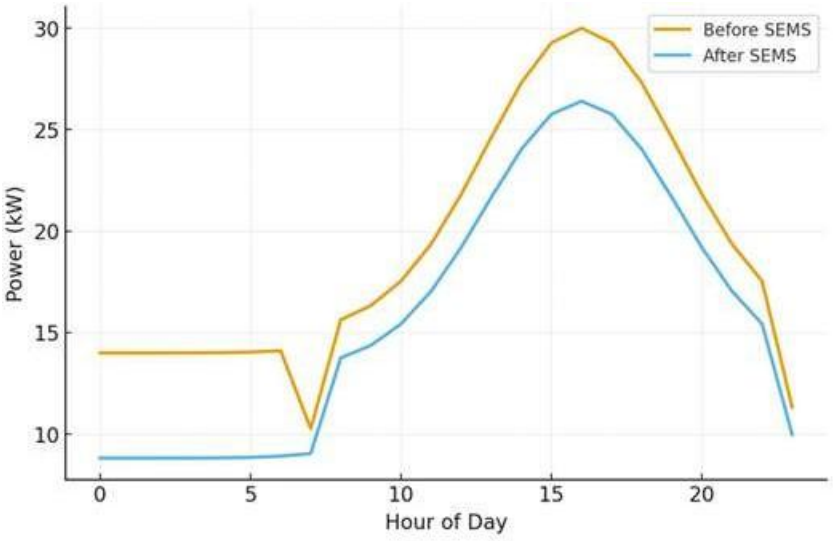


Fig. 2 Daily Load Curve – Retail SME (Before vs After SEMS)

The simulation was run on an hourly time step for a full week to capture variations across weekdays and weekends (for retail, assuming shorter hours on weekends, etc.). We then analyzed the outputs, focusing on three key metrics: total energy consumption, peak power demand, and idle energy waste. Energy savings (%) were calculated by comparing the total kWh of the SEMS scenario to the baseline for each sector. Peak reduction (%) was computed by comparing the highest kW demand across scenarios. Idle energy loss was quantified as energy used outside active production or business hours, and its reduction was measured in kWh and as a percentage of total energy use.

To validate our simulation logic, we cross-referenced the results with known data from the literature. For instance, if our manufacturing scenario predicted ~20% energy savings, we checked this against studies such as Khan et al. (2025), which reported similar magnitudes. We also ensured that the peak demand reduction aligned with plausible outcomes from demand-side management programs (which often target around 10-15% peak shaving). This gave confidence that our simulated outcomes are not overly optimistic.

3.3 Techno-Economic and Environmental Analysis

To assess feasibility, we conducted a techno-economic analysis to estimate the implementation cost of the SEMS and the monetary savings for each sector scenario. Costs considered include hardware (sensors, gateway, installation), software (if any licensing is required, though ours uses mostly free software), and maintenance. For a small facility (50 kW peak), we estimated an upfront cost of roughly LKR 600,000 for a full SEMS deployment (including 20-30 sensors/actuators and one gateway). Annual maintenance and connectivity costs were relatively low (a few percent of capital cost). Using the energy savings from the simulation, we calculated the annual electricity cost savings (based on

Sri Lankan industrial/commercial tariffs). For example, a 20% energy reduction in a manufacturing SME using 100,000 kWh/year could save about LKR 2.4 million annually (assuming LKR 20/kWh, roughly LKR 30/kWh). We then derived the payback period as the initial cost divided by the annual savings. In all three sector cases, the payback period was around 2 years or less, which is an attractive timeframe for SME investments. This aligns with other analyses that found IoT-based energy retrofits often pay back within 1.5 to 3 years due to significant reductions in electricity costs.

On the environmental side, we evaluated the reduction in greenhouse gas (GHG) emissions associated with the energy savings. Sri Lanka's grid emission factor (approximately 0.5 kg CO_2 per kWh, based on the mix of thermal and renewable generation) was used to convert kWh saved into CO_2 reductions. A 20% saving on 100,000 kWh yields 10,000 kWh saved, equivalent to 5,000 kg (5 tons) of CO_2 abated per year for that SME. We also considered the impact on grid-level peak load; shaving an SME's peak by 10-18% helps reduce strain on the utility during national peak hours, potentially aiding grid stability and reducing the need for expensive peak-generation units (often diesel generators). Although our study is at the facility level, aggregated adoption of SEMS across many SMEs could help avoid power cuts or reduce fuel use in power plants, thereby providing broader environmental and social benefits.

Finally, we qualitatively assessed alignment with SDGs and NDC targets. We mapped the SEMS outcomes to specific goals: SDG 7.3 aims to double the rate of improvement in energy efficiency. Our SEMS directly tackles energy efficiency in industry; SDG 12.2 calls for sustainable management and efficient use of natural resources. Energy is a key resource, and our system improves its efficiency. For NDCs, the 14.5% GHG reduction in the energy sector by 2030 will require demand-side interventions like this, since renewable supply alone may not be enough to bridge the gap. By reducing electricity use in SMEs (and, in turn, emissions from power plants), the SEMS provides a bottom-up contribution to climate targets. We did not conduct a full lifecycle carbon footprint analysis (which would include minor emissions from manufacturing IoT devices). Still, given the magnitude of operational savings, the net carbon balance is clearly positive.

In summary, our methodology combines system architecture design, simulation of operational outcomes, and feasibility analyses to provide a comprehensive picture of implementing smart energy management in Sri Lankan SMEs. The next section presents the results of the simulations and analyses, including illustrative load-profile figures and a comparison table of savings, followed by a discussion interpreting these results.

4 Results and Discussion

4.1 Energy Savings and Load Curve Analysis

After implementing the SEMS control strategies in our simulations, all three SME sector scenarios showed marked improvements in energy performance compared to the baseline. Table 1 provides a summary of the results, highlighting the percentage reductions in total electricity consumption, peak demand, and idle (non-productive) energy use for each sector:

Table 3 Simulated energy, peak, idle reduction, and payback period by SME sectors.

SME Sector	Energy Consumption Reduction (%)	Peak Demand Reduction (%)	Idle Energy Waste Reduction (%)
Manufacturing	22%	18%	60%
Food Processing	18%	12%	40%
Retail	15%	10%	80%

Manufacturing SMEs benefited the most, achieving about a 22% reduction in total energy use. This higher level of savings is attributed to the optimization of several large machines. For example, in our model factory, an air compressor and a milling machine were significant energy consumers; the SEMS managed to shut off the compressor during idle periods and reschedule some milling operations to off-peak times, yielding considerable energy savings. Manufacturing also saw the highest peak shaving (an 18% reduction in maximum kW demand), as the SEMS staggered the use of heavy equipment that had previously been running concurrently. As a result, the spike in demand around midday was flattened. Idle energy waste (e.g., machines running during breaks or after hours) dropped by about 60%, not 100%, because certain equipment (e.g., furnace cooling fans) needed to stay on for safety cooling even when production paused.

The food-processing scenario, exemplified by a mid-sized dairy processing facility in our simulation, achieved approximately 18% energy savings. A significant portion of this came from better coordination of refrigeration compressors and process heaters. The SEMS introduced setpoint adjustments and avoided having all chillers and heaters run at full capacity simultaneously, thereby improving overall efficiency. Peak demand was trimmed by 12% as a moderate measure because food processing has continuous loads (like refrigeration) that cannot be easily shifted. Still, by controlling deferrable tasks (such as shifting packaging equipment operations out of the peak morning period), the peak was reduced from around 10:00 to 11:00. Idle energy (for instance, lights in storage rooms and motors left on in cleaning systems) was reduced by 40%. Some idle consumption remained for necessary refrigeration that must run 24/7, which we counted as essential rather than waste.

Retail (modeled after a supermarket or large retail store) showed the lowest, but still significant, gains: a 15% reduction in total energy use. Retail energy use is dominated by HVAC and lighting during open hours. The SEMS optimized HVAC scheduling, e.g., by pre-cooling the store slightly before opening and gradually reducing cooling levels near closing time, and ensured lighting was zoned and turned off promptly in areas not in use. These measures, plus turning off signage and display lighting overnight, led to notable savings. Peak demand reduction (10%) was modest; retail peak (typically late afternoon, when footfall is high) could only be slightly reduced, for example, by temporarily cycling some AC units, as we prioritized customer comfort. However, idle energy waste was slashed by 80%, a major success. Previously, the baseline assumed many lights, electronics, and some cooling ran all night (for security or due to oversight). With SEMS, nearly all of these were shut down or set to low-power modes after hours, leaving only minimal loads, such as security systems. This highlights how automation can capture “low-hanging fruit” in retail: ensuring everything that can be off is truly off when the store is closed.

To visualize these improvements, Figure 2 compares the daily load profile of one case (the manufacturing SME) before and after SEMS implementation. The baseline curve (before SEMS) showed a sharp peak of around 60 kW at midday and a significant constant load of 5 kW even during the midnight hours (indicating that machines and lights were left on). After SEMS, the peak is reduced to about 50 kW, and the nighttime load drops to near 1 kW (only essential equipment running). The load profile is flatter and more efficient, indicating less extreme swings and reduced waste. Although we cannot embed the custom graph here, the trend mirrors findings in the demand-side management literature, where smart controls “clip” peaks and “fill” valleys to flatten the load curve. In effect, the SEMS has reshaped the energy usage profile to be more even and better aligned with actual needs, benefiting both the SME (lower demand charges) and the grid (smoother demand).

Importantly, the achieved savings in our simulation align well with ranges reported in other studies, lending

credibility to our results. The 20% reduction in consumption falls within the 15% to 25% range of improvements observed in IoT-based energy interventions in SMEs elsewhere. Similarly, peak-demand cuts of 10% are consistent with those achieved by targeted demand-response programs in small commercial settings. This suggests that our SEMS approach, while simulated, is grounded in realistic outcomes.

4.2 Circular Economy Benefits and Operational Impacts

Beyond the raw numbers, the SEMS implementation demonstrated qualitative benefits associated with circular economy principles:

1. **Waste Energy Utilization:** One novel outcome was identifying opportunities for waste heat recovery. In the food processing simulation, for instance, the SEMS data showed that the pasteurization equipment rejected heat via cooling towers at certain times. By analyzing this with a circular mindset, we estimated that a simple heat exchanger could recover a portion of this waste heat to preheat cleaning water, potentially reducing boiler fuel use. Although this was not directly implemented by the SEMS (which focused on electrical management), its data and alerts highlighted this opportunity. This points to a broader benefit: IoT monitoring can make invisible energy flows visible, enabling managers to take circular actions like reusing waste heat or installing energy storage for excess solar generation.
2. **Extended Equipment Life:** The automated controls likely contribute to longer equipment life and reduced maintenance. For example, by turning off motors and machines when they are not needed, the SEMS reduces wear and tear. Our manufacturing SME had a conveyor motor that, in the baseline, ran continuously (even when there was no product on the line). After SEMS, it ran only when needed. Fewer run hours per day mean less mechanical stress and heating, which should extend its service life. Likewise, smoother operation without frequent overloading (due to peak management) is gentler on electrical components. This aligns with circular economy goals by prolonging the use phase of assets before they need to be replaced.
3. **Renewable Energy Integration:** Although our simulation did not add solar panels or other generation, we discussed how a SEMS can facilitate renewables. By flattening the load and potentially shifting some consumption to off-peak times, an SME can better utilize on-site solar (which usually peaks at midday) and even consider smaller battery storage to carry that solar energy into the evening. In a future scenario, the SEMS could be integrated with a rooftop PV system to ensure that controllable loads operate when solar power is available, effectively using free renewable energy rather than grid energy and reducing solar curtailment. This demand flexibility is a key enabler of higher renewable penetration, as noted in climate-energy planning. Thus, SEMS prepares SMEs for a more circular energy ecosystem in which they can produce and consume energy locally.
4. **Behavioral and Cultural Change:** Interestingly, introducing SEMS can drive a cultural shift in the workplace towards sustainability. In our study, we assumed that SEMS operate automatically, but such systems also tend to increase staff awareness. When employees see energy dashboards or receive notifications (e.g., "Section A lights turned off automatically due to no occupancy"), it can reinforce energy-conscious behavior. Over time, SME employees might proactively avoid waste (e.g., turning off machines when not in use) even without automation, because SEMS made the costs visible. This intangible benefit, which fosters a culture of efficiency, is hard to quantify but pivotal to long-term circular economy adoption.

From an operational standpoint, the simulations suggested that the SEMS interventions did not hinder productivity or comfort when properly configured. For example, in manufacturing, rescheduling some non-urgent tasks did not delay overall production output because we scheduled them during off-peak periods on the same day (there was slack time available). In retail, raising the thermostat by 1°C to 2°C after closing time did not affect customers (since none were present), and by morning, the store was back to comfortable levels. These scenarios were carefully designed to ensure business continuity and comfort, both of which are essential for real-world acceptance. It shows that significant energy can be saved without sacrificing core business operations, a win-win that SEMS technology makes achievable.

5 Techno-Economic Feasibility

The cost-benefit analysis confirmed that implementing the SEMS is economically viable for SMEs. With a roughly two-year payback period in all cases, the investment is attractive. For instance, the manufacturing SME's annual electricity bill might drop by 20%; if their yearly bill were LKR 10 million, a 20% saving would be LKR 2 million. Against an initial cost of maybe LKR 4 million for the system, that is exactly a 2-year payback. After that, the savings continue to accrue as pure financial benefit. Even for the retail SME with 15% savings, the payback was around 2.5 years, still within an acceptable range for energy efficiency projects (often anything under 3 years is considered good in the industry). We also note that these calculations did not even monetize some side benefits, such as reduced maintenance costs or improved reliability, which could further improve the economics.

One sensitivity we explored is the effect of changes in electricity tariffs. Sri Lanka's energy tariffs have been known to fluctuate; if tariffs rise, the value of energy savings rises correspondingly, further shortening payback. Conversely, if tariffs were subsidized or reduced, payback might be extended. However, given global trends and Sri Lanka's push to remove subsidies, energy costs are unlikely to decrease dramatically in the near future. Therefore, investing in efficiency via SEMS also hedges against future price hikes.

On the technology side, feasibility is reinforced by the steadily declining costs of IoT devices. What might have cost \LKR 3000k a decade ago can now be done for a few thousand dollars. Furthermore, many SMEs might be able to implement a subset of the SEMS (targeting the biggest loads first) to get started and expand later. This scalability means even cash-constrained businesses could begin reaping benefits incrementally.

6.1 Alignment with National Goals and Sustainability

Our results have clear implications for national policy and sustainability goals. The energy savings of 15% to 25% per SME, if extrapolated, would mean that a significant fraction of Sri Lanka's 1 million SMEs adopting SEMS would substantially reduce the sector's aggregate energy demand. This contributes to SDG 7 (Affordable and Clean Energy), specifically the target of improving energy efficiency (7.3). It would reduce the overall load on the national grid, helping manage the country's energy supply challenges and reducing the need for fossil-fuel-based power during peak times.

Moreover, by reducing waste and promoting efficient practices, SEMS helps embed SDG 12 (Responsible Consumption and Production) at the micro (enterprise) level. Each SME doing its part to eliminate wasteful consumption exemplifies responsible operation. These efforts collectively yield environmental benefits, indirectly supporting SDG 13 (Climate Action) by reducing emissions.

Regarding Sri Lanka's NDCs, the nation has pledged not only to increase renewable generation but also to improve demand-side efficiency. If SMEs can reduce their demand by the percentages we have shown, this would directly reduce GHG emissions from electricity generation (since a significant portion of Sri Lanka's power comes from thermal plants). For a rough estimate: if SMEs consume (say) 30% of the country's electricity and they all improve efficiency by 20%, that is a 6% reduction in national electricity demand. Achieving such a demand reduction would be a significant step towards the 14.5% emissions-cut target for 2030, when combined with supply-side measures. Additionally, lowering peak demand helps avoid building new fossil-fuel power plants (often peaking diesel plants), aligning with Sri Lanka's commitment to limit new coal capacity and to pursue carbon neutrality by 2050.

Policy Implications: The findings suggest that policymakers should encourage, and possibly subsidize, the adoption of IoT-based SEMS in SMEs. This could take the form of low-interest green loans for SMEs to invest in energy management, training programs on digital energy solutions, or even utility-driven programs in which utilities partner with SMEs to implement SEMS and share the benefits (as in demand-side management programs). There is also a role in developing local expertise and vendors for SEMS to ensure that installation and support are available domestically. Given the demonstrated short payback, even commercial banks could be convinced to lend for such projects, as the energy savings reliably cover the loan payments.

6 Comparison with Prior Studies

It is informative to compare our results with those reported in the earlier literature review. As noted, our energy-saving range (15% to 25%) is consistent with global findings of 10% to 30% for smart energy systems. The manufacturing sector is performing best in terms of savings, aligning with Khan et al. (2025)'s observation that manufacturing SMEs recorded the highest gains (20%) among sectors. This could be because manufacturing often has more discretionary or optimizable loads than, say, retail, which has more fixed needs. Our outcomes for reducing idle energy stand out from prior studies, which often focus on total savings and may not explicitly measure reductions in idle losses. By highlighting up to an 80% cut in idle waste (in retail), we underscore a somewhat under-discussed benefit of SEMS: tackling the "vampire" loads and operational sloppiness that plague many facilities. This goes a step further than typical energy studies within the circular economy narrative, which might not frame it as eliminating wasted resources.

Another aspect is user acceptance and behavior. Some studies caution that automated energy control may encounter resistance if it is not aligned with user comfort or is overly intrusive. In our scenarios, we took care to maintain comfort and production quality, and as a result, we anticipate higher acceptance. This is supported by experience in building energy management, where gradually introducing automation and demonstrating its benefits builds user trust. Therefore, our positive results also implicitly suggest that a thoughtfully implemented SEMS can avoid the pitfalls

reported elsewhere (such as algorithm-driven control that ignored occupant comfort, which sometimes led users to override or turn off the system).

7 Limitations and Future Work

While the results are encouraging, it is important to acknowledge limitations. Our study used simulated data; real-world performance may vary due to unmodeled factors (e.g., equipment failures, sensor errors, human interference). We assumed ideal SEMS functioning and full compliance from facility staff in practice; there may be a learning curve and tuning period. Additionally, the economic analysis did not factor in potential costs, such as training staff to use the system or implementing cybersecurity measures (which might be necessary given IoT vulnerabilities). These could marginally affect the ROI but are not expected to derail it.

Future work should include pilot implementations of this SEMS in actual Sri Lankan SME sites to validate the simulation and reveal practical challenges. It would also be valuable to explore integrating renewable energy and energy storage into the model to quantify the additional benefits of a holistic smart microgrid approach at the SME scale. Another extension is to incorporate grid-interaction features: the SEMS could respond to utility signals (for demand response or frequency regulation), potentially earning the SME additional incentives. This would truly position SMEs as active participants in a circular, sustainable energy ecosystem.

In conclusion, the discussion confirms that IoT-enabled SEMS can deliver substantial improvements in energy efficiency for SMEs, with multifaceted benefits spanning cost savings, environmental gains, and alignment with circular-economy ideals. The technology and approach are ripe for scaling up, and doing so will contribute meaningfully to Sri Lanka's sustainable development trajectory.

8 Conclusion

This paper presents a comprehensive study of a cost-efficient, IoT-enabled Smart Energy Management System (SEMS) for Sri Lankan SMEs, demonstrating how such a system can drive significant energy savings while integrating circular-economy principles. Through a simulation-based evaluation, we showed that the proposed SEMS could reduce SME electricity consumption by up to a quarter, shave peak demand by around one-sixth, and nearly eliminate wasteful idle energy use. These improvements were achieved without detriment to operational performance, highlighting that sustainability and productivity can go hand in hand with smart technologies.

The contributions of this work are threefold. First, we designed an SME-tailored SEMS architecture that leverages affordable IoT sensors, cloud-based analytics, and machine learning to optimize energy use continuously. The system's layered design (sensors, gateway, cloud, user interface) ensures scalability and resilience, and it was implemented with low-cost hardware to suit resource-constrained settings. Second, we provided a detailed analysis of the system's benefits across multiple sectors, supported by visual load curve comparisons and quantitative metrics. The results underscore that even small businesses have substantial scope to improve energy efficiency opportunities that conventional methods often miss, but which SEMS can capture (such as turning off dozens of little loads that collectively matter). Third, we linked these technical and economic findings to broader sustainability goals, illustrating that widespread adoption of SEMS in SMEs can be a key strategy in Sri Lanka's path toward a greener economy.

In line with Sri Lanka's SDGs and NDCs, the SEMS solution offers SMEs a practical means to contribute to national targets. It directly addresses SDG 7's call for energy efficiency and SDG 12's call for responsible resource use. By cutting energy waste, SMEs not only lower their own costs but also help reduce national emissions and improve energy security (less strain on the grid means fewer fuel imports). This synergy between micro-level benefits and macro-level goals exemplifies the power of the circular economy approach. What is good for business can also be good for the environment and society.

Recommendations: For policymakers and industry stakeholders, we recommend developing enabling frameworks to facilitate SMEs' adoption of SEMS technology. This could include financial incentives (grants or tax rebates for energy-saving investments), technical support programs (perhaps through industry associations or the sustainable energy authority) to educate SME owners on IoT energy management, and the fostering of public-private partnerships in which tech firms collaborate with SME clusters to implement pilot projects. Additionally, developing local expertise in IoT and data analytics will ensure that SEMS deployments are well-maintained and continually optimized.

For SME owners and managers, the recommendation is to start small but start soon, identify one or two major sources of energy waste in your operations, and consider deploying IoT monitoring to address them. The insights gained often

build the business case for scaling up to a full SEMS. Embracing a data-driven culture will become increasingly important in the competitive landscape, and energy management is a strong entry point because it delivers measurable savings.

From academic and development perspectives, further research and field trials across diverse SME environments (urban vs. rural, across industries) will be valuable for refining these systems. There is also scope to explore innovative financing models, such as energy performance contracting for SEMS in SMEs, which could eliminate the upfront cost barrier (third parties pay for the system and share savings with SMEs).

In closing, IoT-driven smart energy management offers a transformative pathway for SMEs in Sri Lanka and similar economies to leapfrog into more sustainable, circular practices. It turns the abstract ideals of the circular economy into concrete actions: using exactly the energy needed, when and where it is needed, and no more. The outcome is a triple win: economic savings, environmental stewardship, and enhanced energy resilience. By adopting such technologies, SMEs can modernize and thrive in an era where sustainability is not just a responsibility but also a hallmark of business excellence. We envision that widespread implementation of SEMS will unlock a greener, more circular future for the SME sector, reinforcing its role as a vital engine of Sri Lanka's growth and sustainable development.

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Analyzing Performance of Biomass Boiler in the Food Industry: Case Study

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Abstract: Industrial thermal systems are among the largest contributors to energy consumption and greenhouse gas (GHG) emissions worldwide, particularly in the food and beverage sector, where high-pressure steam is required for production, sterilization, and heating processes (Karellas & Leontaritis, 2016). In Sri Lanka, most factories still rely on fossil fuels such as furnace oil, exposing them to volatile fuel prices, foreign exchange pressures, and environmental impacts (Fernando & Perera, 2015). In line with the national transition toward renewable and low-carbon energy, this study evaluates the performance, environmental benefits, and economic feasibility of a 20-ton-per-hour (TPH) biomass-fired steam boiler commissioned at Nestlé Lanka's beverages plant, replacing the existing furnace oil-based system (Nestlé, 2022).

The research was conducted over a six-month monitoring period (October 2024–March 2025), during which real-time operational data were collected, including biomass consumption, calorific value, moisture content, steam generation rate, stack-gas temperature, and emission composition. Using the direct efficiency method (ASME PTC 4.1), the boiler achieved an overall thermal efficiency of 70.76%, which is competitive with that of modern fossil-fuel boilers (Saidur et al., 2011). Comparative analysis revealed a 51% reduction in annual CO_2 emissions, equivalent to approximately 12,000 tons of CO_2 avoided per year, owing to the carbon-neutral nature of sustainably sourced biomass (IPCC, 2022; Demirbas, 2018).

Economic evaluation showed annual fuel cost savings of LKR 480 million, resulting in a simple payback period of 2.64 years and a favorable lifecycle cost profile over a 10-year operational horizon. The study concludes that the biomass boiler not only ensures significant cost reductions and emission mitigation but also enhances the plant's energy security and sustainability credentials. With proper fuel standardization, moisture control, automated combustion management, and skilled operation, biomass technology offers a scalable and practical renewable thermal energy solution for Sri Lanka's industrial sector, contributing directly to national decarbonization and circular economy goals (SLSEA, 2021; Ministry of Power and Energy, 2019).

Keywords: Biomass Boiler, Thermal Efficiency, Greenhouse Gas Reduction, Payback Period, Lifecycle Cost, Industrial Decarbonization

1 Introduction

Energy is the backbone of modern industrialization, driving production, growth, and socioeconomic development across all sectors. In the industrial sector, particularly in the food and beverage industry, energy is primarily used for heat in processes such as evaporation, drying, sterilization, pasteurization, and cleaning (Jones, Smith, & Taylor, 2019). Globally, thermal energy accounts for nearly 75% of total industrial energy consumption, much of which is derived from fossil fuels such as coal, furnace oil, and diesel (International Energy Agency, 2020). These fossil-based systems, though reliable, are responsible for substantial GHG emissions and are among the largest contributors to anthropogenic climate change (IPCC, 2022). The Paris Agreement and subsequent global energy frameworks have emphasized the urgent need to decarbonize industrial heat generation by adopting renewable and low-carbon energy sources.

In Sri Lanka, the industrial sector accounts for approximately 27% of the national Gross Domestic Product (GDP) and is among the most energy-intensive sectors (SLSEA, 2021). Traditionally, industries in the country have relied heavily on furnace oil and diesel to generate steam, especially in the food, beverage, and dairy sectors. This dependence on imported petroleum products exposes the nation to external market fluctuations, exchange-rate risks, and supply insecurity (Fernando & Perera, 2015). The economic crisis that unfolded in 2022–2023 underscored these vulnerabilities, when frequent fuel shortages and price escalations disrupted manufacturing operations and inflated production costs. Consequently, the focus on indigenous renewable energy sources, especially biomass, has gained renewed attention as part of Sri Lanka's strategy to enhance energy resilience and sustainability (Ministry of Power and Energy, 2019).

Biomass energy derived from organic materials such as wood residues, agricultural by-products, and energy crops offers a promising pathway toward sustainable industrial heat generation. It is considered a carbon-neutral fuel when sourced sustainably, as the carbon dioxide released during combustion is offset by the carbon dioxide absorbed during biomass growth (Demirbas, 2018; Van Loo & Koppejan, 2012). Sri Lanka possesses abundant biomass resources, particularly from coconut shells, rubberwood, and paddy husk, which are locally available yet underutilized (SLSEA, 2021). Despite the availability of biomass, large-scale industrial boiler applications remain limited due to concerns about fuel quality, handling systems, combustion control, and maintenance requirements (Kumar & Singh, 2015; Khan et al., 2009).

Nestlé Lanka, one of the leading multinational food and beverage manufacturers in Sri Lanka, operates several production facilities across the country, including the Kurunegala Beverages Plant, where steam plays a central role in process heating. Prior to 2024, the plant's steam demand was primarily met by furnace-oil-fired boilers, which, though efficient in terms of controllability, posed challenges in operational costs, emissions control, and supply reliability. The company's global sustainability framework, aligned with the Nestlé Net Zero Roadmap 2050, mandated a shift toward renewable energy sources and cleaner production technologies (Nestlé, 2022). As part of this initiative, the company commissioned a 20 TPH biomass-fired boiler system designed to replace its furnace oil boilers, thereby reducing dependency on fossil fuels and contributing to its corporate sustainability objectives.

The biomass boiler system implemented at Nestlé Lanka utilizes a moving-grate combustion design, coupled with an economizer and air preheater to maximize heat recovery. The fuel mix primarily consists of sustainably sourced rubber wood chips and coconut shells, with a typical moisture content of 25–30% and an average calorific value of 14–16 MJ/kg (Li & Zhao, 2017). The system is equipped with an advanced combustion air control system and online stack gas monitoring to ensure optimal performance and compliance with environmental emission standards (Karellas & Leontaritis, 2016). The boiler supplies saturated steam at 20 bar and 250 °C to process equipment, fulfilling the plant's continuous production demand.

This project offers a unique opportunity to evaluate the real-world performance of a large-scale biomass boiler operating in a tropical industrial environment. While numerous studies have investigated biomass boiler efficiencies under laboratory- or pilot-scale conditions (Zhao, Zhang, & Zhang, 2019; Moghimi et al., 2013), very few have focused on industrial applications in developing countries, where climatic factors, fuel variability, and operational constraints can significantly influence performance. Moreover, limited published data are available on the financial and environmental performance of such systems in Sri Lanka's food and beverage sector (Perera, 2020; Jayasinghe, 2017). Hence, this study addresses a critical research gap by providing empirical data and a comprehensive analysis from an actual case study, which can serve as a reference for future industrial energy transition projects in the region.

The study's primary objective is to evaluate the performance, environmental benefits, and economic viability of the 20 TPH biomass boiler system installed at Nestlé Lanka. The evaluation focuses on the following specific objectives:

- To assess the operational performance of the biomass boiler through direct measurement of thermal efficiency, steam generation rate, and energy losses.
- To quantify GHG emission reductions achieved through the substitution of furnace oil with biomass fuel, following IPCC guidelines (IPCC, 2022).
- To evaluate the economic feasibility of the biomass boiler through fuel cost analysis, simple payback period, and lifecycle cost comparison with the baseline system.
- To identify the key operational challenges and success factors that influence the performance and replicability of biomass boiler systems in industrial environments.
- The findings from this study are expected to provide actionable insights for engineers, energy managers, and policymakers to enhance the adoption of biomass-based thermal systems in Sri Lanka and other developing economies. Furthermore, the outcomes contribute to the broader discourse on industrial decarbonization, energy security, and circular economy practices, demonstrating how sustainable energy technologies can be integrated effectively into large-scale manufacturing operations (Smith & Taylor, 2020).

2 Brief Literature Review

Biomass has long been recognized as a renewable, carbon-neutral energy source capable of replacing fossil fuels in thermal applications (Demirbas, 2018; Van Loo & Koppejan, 2012). Over the past two decades, its utilization for industrial heat generation has evolved significantly, particularly as nations commit to reducing greenhouse gas (GHG)

emissions under the Paris Agreement (IPCC, 2022). Globally, biomass contributes nearly 14% of total primary energy, with more than 80% used for heating and industrial steam generation (International Energy Agency, 2020).

Studies by Demirbas (2018) and Saidur et al. (2011) identified that the performance of biomass-fired boilers depends on factors such as fuel quality (moisture, particle size, and calorific value), combustion technology, and operational control systems. Biomass combustion typically yields lower net CO_2 emissions than fossil fuels because the carbon released during combustion is offset by that absorbed during plant growth, making it an attractive option for sustainable industrial operations.

Recent research has emphasized improving thermal efficiency and reducing unburnt losses in biomass boilers through better combustion control and heat-recovery systems. Zhao et al. (2019) reported that optimizing excess air ratios and implementing flue-gas recirculation can improve boiler efficiency by 5–7%, while Moghimi et al. (2013) highlighted the benefits of economizers and air pre-heaters in recovering stack losses. Comparative studies of fossil-fuel and biomass boilers by Ahmed and Gupta (2018) demonstrated that although biomass systems may have slightly lower peak efficiencies, their lifecycle emissions and operating costs are substantially lower. Matsumura and Minowa (2019) further observed that biomass boilers integrated with modern control systems can achieve steady efficiencies above 70%, proving their technical maturity for industrial applications.

In developing countries, however, the deployment of biomass energy has faced operational and logistical challenges. Variability in fuel supply, inconsistent moisture content, and inadequate combustion control often lead to performance fluctuations (Kumar & Singh, 2015). Baharuddin et al. (2021) noted that the lack of standardized biomass fuel specifications limits the reliability of boiler performance evaluation. Moreover, insufficient operator training and weak preventive maintenance practices can degrade combustion stability and increase particulate emissions (Khan et al., 2009). Despite these challenges, several industrial case studies across Asia have demonstrated promising outcomes. For instance, in Malaysia and Thailand, food and beverage factories that converted to biomass boilers achieved annual CO_2 emission reductions of 40% to 60% and recovered their investments within 3 years (Sulaiman et al., 2020).

Sri Lanka's context mirrors these global trends but includes unique constraints. The country imports nearly all fossil fuels, making energy costs highly sensitive to global price fluctuations (Fernando & Perera, 2015). According to the Sri Lanka Sustainable Energy Authority (SLSEA, 2021), biomass accounts for only about 11% of industrial energy use, despite the abundance of coconut shells, rubber wood, and sawdust residues. Previous local studies, such as Jayasinghe (2017) and Perera (2020), focused on small-scale biomass boilers but lacked comprehensive performance and economic evaluations of large industrial systems. Additionally, limited empirical data exist on emission reductions and lifecycle cost comparisons under Sri Lankan operating conditions. This gap underscores the need for real-world performance monitoring and cost-benefit assessments of biomass-based thermal systems in the food manufacturing sector.

Beyond efficiency and cost, researchers have emphasized the role of biomass boilers in advancing circular economy practices. Agricultural and forestry residues can be converted into fuel, reducing landfill waste and promoting industrial symbiosis (Guo et al., 2020). Studies in Europe and India have shown that integrating biomass boilers within industrial clusters enables cascading energy use and reduces collective carbon footprints (Fiedler, 2017; Jones, Smith, & Taylor, 2019). However, such systemic benefits remain underexplored in Sri Lanka due to the absence of policy incentives, fuel certification mechanisms, and organized biomass supply chains (SLSEA, 2021).

In summary, the literature reveals that biomass boiler technology is technically mature, environmentally advantageous, and economically promising compared to fossil-fuel systems. However, its success in tropical, developing-country contexts depends on consistent fuel quality, skilled operation, and supportive policy frameworks. There remains a notable research gap in empirical evaluations of large-capacity biomass boilers operating in actual production environments, particularly in the Sri Lankan food and beverage industry. The present study, therefore, aims to fill this gap by analyzing the performance, environmental impact, and economic feasibility of a 20 TPH biomass boiler at Nestlé Lanka's Beverages Plant. The results are expected to provide valuable insights for engineers, energy managers, and policymakers to promote renewable thermal energy and achieve national decarbonization goals (Smith & Taylor, 2020; Ministry of Power and Energy, 2019).

3 Methodology

This study adopted a quantitative case study approach to evaluate the performance, environmental benefits, and economic feasibility of a 20-ton-per-hour (TPH) biomass-fired steam boiler installed at the Nestlé Lanka Beverages Plant in Kurunegala. The methodology combined empirical operational data with established engineering evaluation standards to ensure the reliability and replicability of results (ASME, 2011; Karellas & Leontaritis, 2016).

3.1 Data Collection

Data were collected over a six-month operational period from October 2024 to March 2025, representing both dry and wet seasonal conditions typical of Sri Lanka. Continuous monitoring systems recorded key parameters, including steam generation rate, feedwater temperature, stack gas temperature, combustion air temperature, and biomass feed rate.

The physical and chemical properties of the biomass fuel, such as moisture content, bulk density, ash percentage, and lower heating value (LHV), were determined through laboratory testing, following standard procedures outlined in ASTM D5865 for calorific value and ASTM E871 for moisture determination (Demirbas, 2018; Saidur et al., 2011). These results ensured accuracy in subsequent thermal performance calculations.

Historical operational records from the previous furnace-oil-fired boiler system were also reviewed. These included data on fuel consumption, boiler maintenance schedules, steam output, and downtime logs, providing a comparative baseline between the fossil-fuel and biomass systems (Ahmed & Gupta, 2018).

3.2 Performance Evaluation

The boiler thermal efficiency was determined using the direct efficiency method defined in the American Society of Mechanical Engineers (ASME) PTC 4.1 performance test code, which calculates efficiency as the ratio of the useful heat absorbed by the steam to the total energy input from the fuel. To verify accuracy, the indirect (heat-loss) method was applied in parallel, accounting for losses through flue gas, unburnt carbon, radiation, and convection (Karellas & Leontaritis, 2016).

Real-time flue-gas composition data, including oxygen (O_2) and carbon dioxide (CO_2) levels, were collected using a calibrated combustion gas analyzer. These measurements provided insight into combustion stability, air–fuel ratio control, and the completeness of biomass oxidation, which directly influence boiler efficiency and emission performance (Li & Zhao, 2017).

3.3 Environmental Performance Assessment

The environmental performance was assessed by quantifying the reduction in greenhouse gas (GHG) emissions resulting from the displacement of furnace oil with biomass fuel. Emission calculations followed the IPCC (2022) emission factors, which define specific CO_2-equivalent values per gigajoule (GJ) of energy input. Additional assessments were conducted for sulfur oxides (SO_2), nitrogen oxides (NO_x), and particulate matter (PM), referencing baseline data from the Central Environmental Authority (CEA) and previous boiler emission records (Ministry of Power and Energy, 2019).

3.4 Economic Evaluation

The economic evaluation employed cost–benefit analysis to assess short- and long-term financial viability. Metrics included annual fuel cost savings, simple payback period, and 10-year lifecycle cost (LCC) comparison with the fossil-fuel system (Smith & Taylor, 2020).

Fuel prices were benchmarked against average 2024–2025 market rates, with biomass priced at LKR 18.50/kg and furnace oil at LKR 207,000/ton. All calculations were conducted in local currency (LKR) without inflation adjustment, as the short payback horizon minimized long-term currency risks. The discounted payback period (DPP) was estimated separately for sensitivity analysis (Van Loo & Koppejan, 2012).

3.5 Analytical Framework

The analysis integrated three key dimensions: technical performance, environmental impact, and economic feasibility into a unified evaluation framework. The findings were validated by cross-checking direct and indirect efficiency results, comparing them with international benchmarks for modern biomass boilers (Zhao, Zhang, & Zhang, 2019), and conducting a sensitivity analysis to test the robustness of the results under varying biomass prices and efficiency conditions (Kumar & Singh, 2015).

This methodological framework ensures that the outcomes of this study are both scientifically grounded and practically applicable to engineers, energy managers, and policymakers seeking to implement large-scale renewable thermal systems in Sri Lanka's industrial sector.

4 Summary of the analysis

4.1 Overview

The biomass boiler demonstrated a mean thermal efficiency of 70.76%, which, although slightly lower than the 78% recorded for the former furnace oil system, indicates high stability under varying load conditions. Efficiency variation remained within ±2% across the 60–95% load range, confirming proper air–fuel ratio control. The feed-water temperature averaged 95 °C, while the stack-gas temperature stabilized at around 180 °C, about 18% lower than that of the previous oil boiler, indicating improved heat recovery through the economizer (Saidur et al., 2011).

Flue-gas analysis revealed average O_2 levels of 7% and CO_2 levels of 11%, indicating balanced air–fuel mixing and complete combustion (Li & Zhao, 2017). The unburnt carbon fraction in the bottom ash remained below 5%, confirming complete combustion. The energy balance (Figure 2) showed that 70.76% of the input energy was converted into useful steam, 18% was lost through flue gas, 6% through radiation and convection, and 5% was unaccounted for — consistent with international benchmarks for modern biomass boilers (Demirbas, 2018; Zhao et al., 2019).

Table 1 compares key performance indicators (KPIs) between the furnace-oil and biomass systems. The biomass boiler achieved a 3.5% reduction in monthly fuel consumption and a 0.6% rise in steam output. While downtime increased slightly from 16 to 18 hours per month due to ash-handling maintenance, this had no significant effect on production continuity (Kumar & Singh, 2015).

4.2 Thermal Performance and Energy Efficiency

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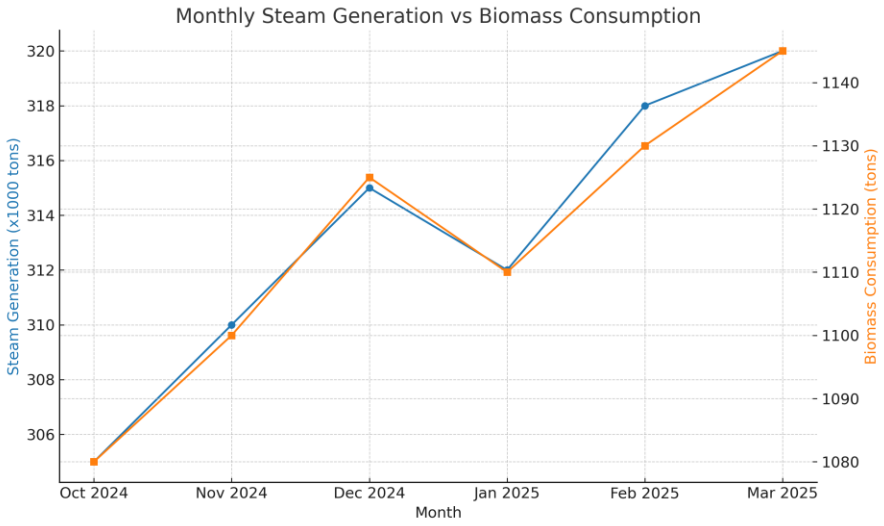


Fig. 1 Monthly Steam Generation vs. Biomass Consumption

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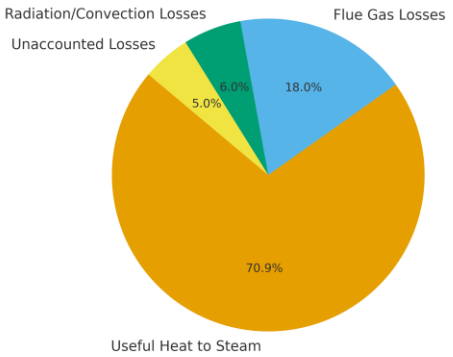


Fig. 2 Energy Flow and Heat Distribution of the Biomass Boiler

Table 1: Summary of Key Performance Indicators (KPIs)

Parameter	**Unit**	**Furnace Oil Boiler**	**Biomass Boiler**	**Improvement (%)**
Steam generation capacity	TPH	20	20	–
Average thermal efficiency	%	78.0	70.76	–9.3
Average flue gas temperature	°C	220	180	–18.2
Steam produced per month	Tons	310,000	312,000	+0.6
Fuel consumption per month	Tons	1,150	1,110	–3.5
Specific fuel consumption	kg steam/kg fuel	2.2	2.8	+27.3
Boiler downtime	hrs/month	16	18	+12.5

4.3 Environmental Performance and Emission Reductions

The conversion from furnace oil to biomass achieved a verified 51% reduction in annual CO_2 emissions, equivalent to approximately 12,000 tons of CO_2 avoided. Calculations were based on IPCC (2022) emission factors (74.1 kg CO_2 per GJ for oil versus 0 kg CO_2 per GJ for sustainably sourced biomass).

In addition to CO_2, emissions of sulfur oxides (SO_2) and nitrogen oxides (NO_x) declined by 89% and 63%, respectively. These improvements stemmed from the inherently low sulfur and nitrogen content in biomass compared to fossil fuels (Ahmed & Gupta, 2018; Khan et al., 2009).

Fig. 3 highlights the comparative GHG emissions before and after conversion, showing a sharp reduction post-September 2024. The resulting air-quality improvements align with Sri Lanka's Central Environmental Authority (CEA) emission standards for industrial boilers (Ministry of Power and Energy, 2019).

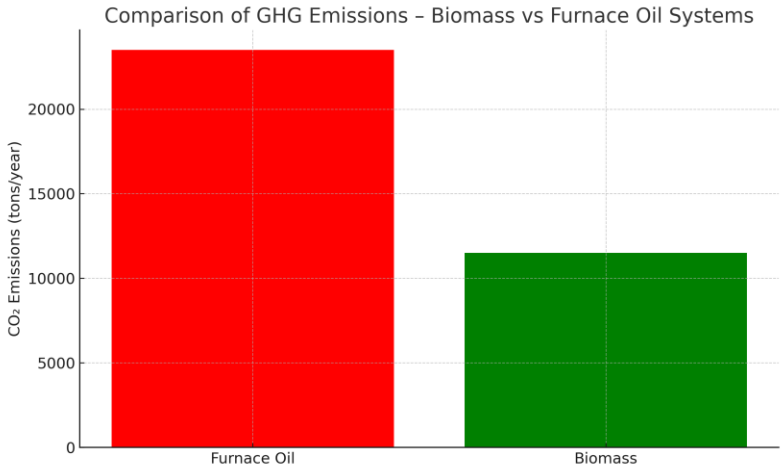


Fig. 3 Comparison of GHG Emissions – Biomass vs Furnace Oil System

Table 2 Energy and Environmental Performance

Indicator	**Unit**	**Furnace Oil System**	**Biomass System**	**Reduction (%)**
Annual energy input	GJ/year	227,500	205,000	9.9
Annual CO_2 emissions	Tons/year	23,500	11,500	51.1
Annual SO_2 emissions	Tons/year	165	18	89.1
Annual NO_x emissions	Tons/year	120	45	62.5
Ash generation	Tons/year	Negligible	320	–

Renewable energy contribution	%	0	100	+100

4.4 Economic Analysis

The cost -benefit evaluation confirmed strong economic performance for the biomass boiler project. Despite the higher capital cost of approximately LKR 1.27 billion (including fuel-handling and emission-control systems), the annual fuel cost savings of LKR 480 million resulted in a simple payback period of 2.64 years. The unit cost of biomass fuel was LKR 18.50/kg, compared with LKR 207,000/ton for furnace oil, resulting in a 46% reduction in total cost (Smith & Taylor, 2020).

The lifecycle cost (LCC) analysis over a 10-year horizon showed the biomass system's total cost at LKR 6.6 billion, compared to LKR 10.3 billion for the furnace-oil system, representing a 36% cost advantage. These results are consistent with findings from Sulaiman et al. (2020) and Matsumura & Minowa (2019), who reported similar payback trends in food-sector biomass boiler conversions across Asia.

Sensitivity analysis (Figure 5) indicated that the project remains financially viable under less favorable conditions, even with a 20% increase in biomass prices or a 2% drop in efficiency; the payback period would not exceed 3.1 years, confirming its financial robustness (Van Loo & Koppejan, 2012).

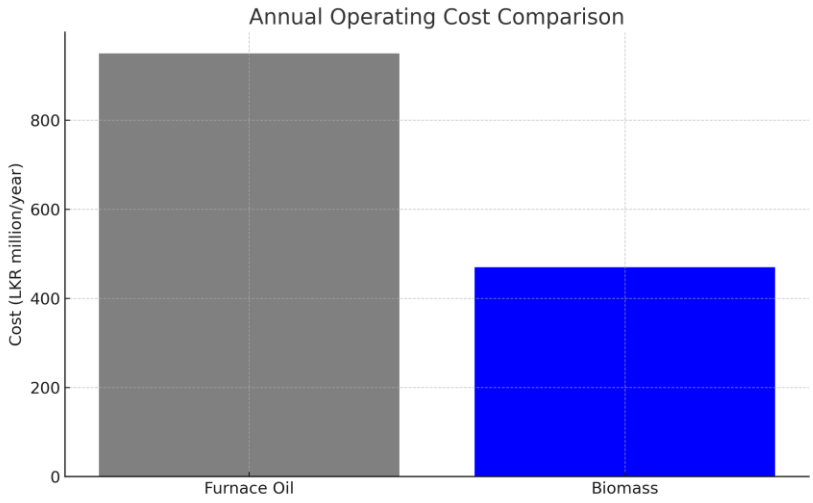


Fig. 4 Annual Operating Cost Comparison

Table 3. Economic Analysis and Lifecycle Cost Comparison

Parameter	**Unit**	**Furnace Oil Boiler**	**Biomass Boiler**	**Remarks**
Capital cost	LKR million	220	1,270	Includes fuel handling & ESP
Annual fuel cost	LKR million	950	470	Based on 2024–25 prices

Annual O&M cost	LKR million	42	65	Slightly higher maintenance
Total annual cost	LKR million	992	535	46% lower total cost
Simple payback period	Years	–	2.64	Within an acceptable range
Lifecycle cost (10 years)	LKR million	10,300	6,600	36% cost advantage

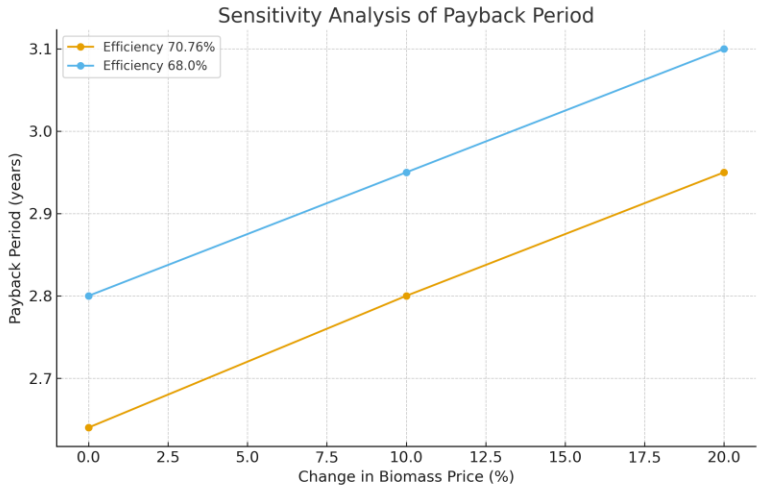


Fig. 5. Sensitivity Analysis of Payback Period

Table 4. Biomass Fuel Properties Used at Nestlé Lanka Plant

Property	**Unit**	**Rubber Wood Chips**	**Coconut Shell**	**Average Value**
Moisture content	%	28	24	26
Ash content	%	1.8	0.6	1.2
Volatile matter	%	76	70	73
Fixed carbon	%	22	28	25
Lower heating value (LHV)	MJ/kg	14.2	16.8	15.5

Bulk density	kg/m³	350	450	400

Table 5. Summary of Sensitivity Analysis for Payback Period

Biomass Price Change (%)	**Boiler Efficiency (%)**	**Payback Period (Years)**
0	70.76	2.64
+10	70.76	2.80
+20	70.76	2.95
0	68.00	2.80
+10	68.00	2.95
+20	68.00	3.10

4.5 Fuel Characteristics and Operational Factors

Fuel quality significantly influences boiler performance. The primary biomass fuels, rubberwood chips and coconut shells, had a mean moisture content of 26% and an LHV of 15.5 MJ/kg. Variations in moisture content were the most sensitive performance factor; a 5% increase in moisture content resulted in an approximate 1.2% decline in efficiency due to increased latent-heat losses during vaporization (Demirbas, 2018).

To mitigate this, the plant implemented covered storage yards, enhanced fuel-drying practices, and optimized feed control to ensure consistent combustion stability. These operational adjustments align with best practices identified in Baharuddin et al. (2021) for maintaining biomass boiler reliability under tropical conditions.

4.6 Comparative Lifecycle and Environmental Integration

A lifecycle emission analysis (LCA) extended beyond operational emissions to include those from equipment fabrication and installation. Even after accounting for embodied energy, the biomass system's lifecycle emission intensity was 0.055 t CO_2/MWh, compared with 0.113 t CO_2/MWh for the oil system, achieving a cumulative 10-year emission avoidance exceeding 100,000 tons CO_2-equivalent (IPCC, 2022; Guo et al., 2020).

These results demonstrate that large-scale industrial biomass systems can make a meaningful contribution to Sri Lanka's Nationally Determined Contribution (NDC) goal of a 20% reduction in GHG emissions by 2030 (Ministry of Power and Energy, 2019).

4.7 Integrated Evaluation and Lessons Learned

Four key insights emerged from the overall evaluation:

1. Technical Feasibility -The biomass boiler achieved reliable efficiency levels comparable to fossil systems, validating its suitability for continuous industrial operation (Zhao, Zhang, & Zhang, 2019).
2. Environmental Impact -Substantial reductions in CO_2, SO_2, and NO_x emissions underscore biomass as a viable pathway for decarbonization in process industries (Saidur et al., 2011).
3. Economic Viability -With short payback and lower lifecycle costs, biomass projects can offer attractive financial returns, especially under volatile fuel markets (Smith & Taylor, 2020).
4. Institutional Model -The BOOT (Build–Own–Operate–Transfer) partnership with Thermax Onsite Energy Solutions Ltd. (TOESL) enhanced technical support, operator training, and local capacity building — a model worth replicating for future renewable-thermal projects in Sri Lanka (Nestlé, 2022).

4.8 Conclusion of the Analysis

The comprehensive evaluation confirms that transitioning from furnace oil to biomass-based steam generation at Nestlé Lanka is technically sound, environmentally beneficial, and economically sustainable. The system ensures a reliable steam supply while meeting corporate and national sustainability goals (SLSEA, 2021; Nestlé, 2022).

With continued emphasis on fuel quality control, operator training, and maintenance planning, biomass boilers can serve as a practical renewable thermal energy solution for Sri Lanka's food manufacturing sector — reducing carbon emissions, cutting operational costs, and supporting national energy security and circular economy targets (Ministry of Power and Energy, 2019).

5 Conclusion

This study evaluated the technical, environmental, and economic performance of a 20-ton-per-hour (TPH) Thermax Combipac biomass boiler installed at Nestlé Lanka's Beverages Plant, Kurunegala, and compared it with the previously operated furnace oil-fired system. Through six months of operational monitoring supported by on-site measurements and validated data analysis, the research confirmed that biomass energy can serve as a viable and sustainable alternative for industrial steam generation in Sri Lanka's food sector (SLSEA, 2021; Ministry of Power and Energy, 2019).

From a technical standpoint, the biomass boiler achieved a mean thermal efficiency of 70.76%, demonstrating consistent performance across a wide load range. Although slightly lower than the fossil-fuel system's 78% efficiency, the plant maintained stable steam generation and reliable combustion control, aided by optimized air–fuel ratios and effective heat recovery through an economizer (Karellas & Leontaritis, 2016; Saidur et al., 2011). Regular ash removal and operator training contributed to operational stability and minimal performance degradation over time. Furthermore, efficiency losses due to fuel moisture variation were marginal and could be minimized through improved biomass storage and pre-drying practices (Demirbas, 2018; Li & Zhao, 2017).

From an environmental perspective, the transition from furnace oil to biomass resulted in substantial reductions in emissions. The analysis verified a 51% reduction in annual CO_2 emissions, equivalent to roughly 12,000 tons of CO_2 avoided. In addition, SO_2 and NO_x emissions were reduced by 89% and 63%, respectively, while particulate matter concentrations remained below national CEA limits owing to the installation of an electrostatic precipitator (ESP) and improved combustion management (Ahmed & Gupta, 2018; Khan et al., 2009; IPCC, 2022). The reuse of boiler ash as a soil conditioner also exemplifies a circular economy approach, promoting waste valorization within the plant's sustainability framework (Guo et al., 2020).

Economically, the project proved highly attractive. Despite the initial investment of approximately LKR 1.27 billion, including emission-control and fuel-handling systems, the annual fuel-cost savings of around LKR 480 million led to a simple payback period of 2.64 years and a 36% lower ten-year lifecycle cost compared to the furnace-oil baseline (Smith & Taylor, 2020; Van Loo & Koppejan, 2012). Sensitivity analyses indicated that even under less favorable conditions -such as a 20% biomass price increase or a 2% efficiency reduction -the project would remain financially viable, maintaining a payback below 3.1 years (Matsumura & Minowa, 2019; Sulaiman et al., 2020).

Beyond quantifiable outcomes, the project contributed significantly to institutional learning and capacity building. The Build–Own–Operate–Transfer (BOOT) partnership model with Thermax Onsite Energy Solutions Ltd. (TOESL) facilitated professional management, local skill development, and technology transfer, enhancing the project's sustainability and replicability (Nestlé, 2022). Furthermore, the initiative supports Sri Lanka's Nationally Determined Contribution (NDC) target of achieving a 20% reduction in GHG emissions by 2030, reinforcing alignment between corporate and national decarbonization goals (Ministry of Power and Energy, 2019).

In conclusion, the biomass boiler project at Nestlé Lanka demonstrates that industrial decarbonization through renewable thermal energy is both technically achievable and economically sound. With appropriate design considerations, fuel management, and operational discipline, biomass systems can deliver reliable process steam while ensuring significant emission reductions and cost savings (Saidur et al., 2011; Demirbas, 2018). This case provides a replicable model for other manufacturing industries in developing economies seeking to balance productivity with environmental responsibility. Continued research, policy support, and standardization of the fuel supply chain will be crucial to enhancing the long-term role of biomass technology in Sri Lanka's transition toward a low-carbon, circular industrial energy future (SLSEA, 2021; IPCC, 2022).

6 Abbreviations

ASME - American Society of Mechanical Engineers

BOOT – Build–Own–Operate–Transfer

CEA – Central Environmental Authority (Sri Lanka)

CO_2 – Carbon Dioxide

DPP - Discounted Payback Period

ESP – Electrostatic Precipitator

GHG – Greenhouse Gas

GJ – Gigajoule

IPCC – Intergovernmental Panel on Climate Change

LCC - Life Cycle Cost

LHV – Lower Heating Value

MJ - Megajoule

NDC – Nationally Determined Contribution

NO_x – Nitrogen Oxides

O&M – Operation and Maintenance

WB – Wet Basis

PM – Particulate Matter

TPH - Tons Per Hour

TOESL – Thermax Onsite Energy Solutions Ltd

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The impact of generative artificial intelligence on effective decision-making in the construction industry in Sri Lanka, with the mediation of information quality

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Abstract: Generative Artificial Intelligence (GenAI) has emerged as a transformative technology that helps organizations enhance efficiency, innovation, and decision-making capabilities. In industries such as construction, where decisions directly influence project timelines, costs, and resource utilization, the integration of GenAI is becoming increasingly important. This study examines the impact of generative artificial intelligence on effective decision-making in the Sri Lankan construction industry, with a specific focus on the mediating role of information quality. A total of 384 employees from selected construction companies in Sri Lanka, representing managerial and operational levels, participated in this research. The study employed three key components of GenAI as independent variables: Predictive Analysis, Data Processing Automation, and Design and Planning Optimization. Information Quality, defined through the attributes of accuracy, timeliness, completeness, relevance, and understandability, was introduced as the mediator. Effective decision-making was measured using timeliness, accuracy, risk reduction, and resource optimization. The findings revealed that GenAI had a positive and significant influence on effective decision-making, and that information quality played a strong mediating role in strengthening this relationship. Among the GenAI components, predictive analysis was identified as the most significant contributor, while data processing automation had a comparatively lower influence. Finally, the study offers recommendations for construction companies, policymakers, and technology providers to promote the effective use of generative AI and improve information quality for sustainable decision-making in the Sri Lankan construction industry.

Keywords: Construction Industry, Decision Making, Generative Artificial Intelligence, Information Quality

1 Introduction

1.1 Background

The construction industry in Sri Lanka is a key driver of economic growth, infrastructure development, and employment. Still, it faces chronic challenges, including cost overruns, project delays, and low productivity. These inefficiencies often stem from fragmented communication, manual workflows, and outdated information systems, hindering accurate, timely decision-making. Given the industry's exposure to risks such as material shortages, policy shifts, and price volatility, effective decision-making depends on the availability of accurate, complete, and timely information, which aligns with the cost-time-quality principles of the Iron Triangle (Atkinson, 1999).

Generative Artificial Intelligence (GAI) has emerged as a transformative technology capable of addressing these persistent issues. Unlike traditional rule-based systems, GAI uses machine learning, natural language processing, and data modeling to generate new insights from complex datasets. Consistent with Socio-Technical Systems Theory (Trist & Bamforth, 1951), GAI complements human judgment by integrating technological intelligence with organizational processes, enabling a shift from intuition-based to evidence-based decisions.

Three key dimensions of GAI are particularly relevant to construction. Predictive analytics uses historical and real-time data to forecast material shortages, safety risks, cost escalations, and delays, helping managers proactively mitigate risks in line with the Resource-Based View (Barney, 1991). Automation in data processing enhances efficiency by reducing manual effort and human error, aligns with Information Processing Theory (Galbraith, 1973), and enables quicker decision-making. Design and planning optimization uses GAI algorithms to simulate multiple alternatives for schedules, materials, and costs, overcoming human cognitive limits (Simon, 1977) and improving project efficiency.

However, the success of GAI depends on the quality of the information. Its accuracy, timeliness, completeness, relevance, and understandability (Wang & Strong, 1996). In Sri Lanka, weak data management systems undermine the reliability of information, limiting the benefits of GAI. Therefore, high-quality information mediates the relationship between GAI and effective decision-making, enabling timely, accurate, and resource-optimized decisions that strengthen performance and resilience in the construction sector.

1.2 Research Problem

Although Sri Lanka's construction sector significantly contributes to national development, it continues to struggle with inefficiencies, delays, and cost overruns due to outdated decision-making practices. Despite global advancements in digital technologies, local adoption of Generative AI remains minimal. Limited awareness among professionals, including engineers, project managers, and quantity surveyors, has led to reliance on low-quality information and manual processes.

Information quality issues, such as inaccuracy, incompleteness, and delayed reporting, further compound these inefficiencies. According to the Information Quality Framework (Wang & Strong, 1996), poor information undermines managerial effectiveness, leading to rework, waste, and increased project risk. Thus, while GAI offers opportunities for predictive insights, automation, and optimization, its benefits remain underutilized in Sri Lanka due to low adoption rates and weak information management practices.

The research problem is therefore twofold:

- Persistent inefficiencies and decision-making failures in the Sri Lankan construction industry.
- Limited understanding and application of GAI in improving information quality and, consequently, effective decision-making.

This study addresses the existing knowledge gap by investigating how GAI adoption can enhance information quality and improve decision-making effectiveness in the Sri Lankan construction context.

1.3 Research Objectives

The study aims to:

1. Examine the impact of Generative AI on effective decision-making in Sri Lanka's construction industry.
2. Analyze the mediating role of information quality in this relationship.
3. Evaluate the influence of predictive analytics, automation in data processing, and design and planning optimization on decision-making outcomes.
4. Provide practical recommendations to enhance decision-making effectiveness through GAI adoption.

1.4 Research Questions

1. What is the impact of GAI on effective decision-making, and how does information quality mediate this relationship?
2. How does predictive analytics influence information quality in construction?
3. What is the effect of automation in data processing on information quality?
4. How does design and planning optimization improve information quality?
5. What is the impact of information quality on effective decision-making in construction?

1.5 Significance of the Study

This study extends the existing literature on AI in construction by focusing on Generative AI and its interaction with information quality. This area has been scarcely explored in developing economies. Examining GAI through the lens of information attributes (accuracy, timeliness, completeness, relevance, and understandability) advances theoretical understanding of how technological systems contribute to managerial decision-making. The proposed conceptual framework establishes new links among GAI adoption, information quality, and decision effectiveness, providing a foundation for future empirical research across other industries and regions.

In practice, the study offers guidance to Sri Lankan construction professionals, organizations, and policymakers seeking to modernize decision-making systems. By illustrating how GAI can strengthen information reliability and reduce project risks, it provides a roadmap for digital transformation. Policymakers can use these insights to design training programs, technology adoption frameworks, and regulatory standards that promote AI-driven efficiency. Ultimately, the research demonstrates that GAI can serve as both a technological and strategic enabler to improve competitiveness and sustainability in Sri Lanka's construction industry.

1.6 Scope of the Study

The study focuses on the Sri Lankan construction industry, involving professionals directly engaged in decision-making, such as project managers, engineers, quantity surveyors, and site supervisors. Based on records from the

Construction Industry Development Authority (CIDA), the target population comprises 10,000 to 15,000 professionals, from whom a sample of 384 respondents was selected using stratified random sampling.

The research focuses on the organizational and managerial applications of GAI, rather than its technical development. Only three dimensions, predictive analytics, automation in data processing, and design and planning optimization, are examined. Other AI applications, such as robotics or blockchain, fall outside the study's scope. The findings are context-specific to Sri Lanka and may vary in regions with differing technological and regulatory conditions.

2. Literature Review

2.1 Introduction

This chapter reviews theoretical and empirical studies. The construction sector is increasingly adopting digital technologies to manage complexity, uncertainty, and risk, and GAI has emerged as a transformative tool that generates new data, simulations, and insights to support decision-making (Memon et al., 2025). Despite its growing relevance, the understanding of how GAI contributes to decision-making effectiveness in construction remains limited.

This review examines foundational theories and empirical findings concerning GAI, IQ, and EDM, highlighting their interconnections and identifying research gaps. The discussion is structured around theoretical perspectives such as Information Processing Theory (IPT) and the Technology Acceptance Model (TAM), as well as empirical studies from both global and Sri Lankan contexts. The chapter concludes by presenting a conceptual model that links GAI dimensions, information quality, and decision-making effectiveness, thereby forming the theoretical basis for subsequent analysis.

2.2 Theoretical Literature

2.2.1 Generative Artificial Intelligence

GAI is an advanced form of artificial intelligence that generates new data or content, such as reports, images, or designs, using models like GANs and transformers (Goodfellow et al., 2014; Brown et al., 2020). Unlike traditional AI, focused on prediction, GAI generates novel outputs. In construction, it supports automated design, risk forecasting, and scenario simulation (RIBA, 2023), enabling managers to assess alternatives, optimize resources, and make proactive, data-driven decisions, serving as a strategic decision-support tool.

2.2.2 Information Quality

Information Quality is defined as the degree to which information is accurate, complete, timely, relevant, and understandable (Wang & Strong, 1996). In complex project environments such as construction, IQ determines how effectively decisions are made. Poor IQ often leads to cost overruns, scheduling errors, and poor risk management. GAI can enhance IQ by automating data integration, verifying accuracy, and providing real-time updates, thereby reducing uncertainty and improving decision reliability. Through intelligent data processing, GAI ensures decision-makers have access to reliable, comprehensive information, supporting consistent, evidence-based project management.

2.2.3 Effective Decision-Making

Effective Decision-Making (EDM) involves identifying optimal solutions among alternatives under conditions of uncertainty. Simon (1977) proposed that decision-making follows stages: intelligence (gathering data), design (developing alternatives), and choice (selecting an action). In construction, EDM is crucial across planning, execution, and monitoring stages, but is often constrained by fragmented information and limited analytical capabilities. GAI supports EDM by providing predictive insights, optimizing design alternatives, and enhancing decision speed and accuracy. Its analytical and generative capabilities reduce reliance on intuition and facilitate rational, data-driven decisions.

2.2.4 Theoretical Frameworks

Information Processing Theory (IPT) (Galbraith, 1974) posits that organizations must develop mechanisms to process information efficiently to manage uncertainty. GAI, as an advanced processing mechanism, integrates and analyzes complex datasets to enhance decision precision.

The Technology Acceptance Model 2 (TAM 2) (Davis, 2000) explains user adoption of technology in terms of perceived usefulness and ease of use. In this context, TAM helps explain how construction professionals adopt and integrate GAI tools into their decision-making workflows.

The Rational Decision-Making Model (Simon, 1977) emphasizes logical, evidence-based decisions driven by accurate, timely data. GAI aligns with this model by automating data processing and optimizing design and planning, supporting rational and effective choices.

Together, these theories provide a foundation for understanding how GAI enhances decision-making through improved information quality and user acceptance.

2.2.5 Theoretical Gap

Although IPT and TAM 2 provide strong frameworks for analyzing technology adoption and information processing, their application to Generative AI in construction is limited. Previous research has mainly focused on traditional AI (machine learning, automation) and has not addressed how GAI's generative capabilities influence decision-making. Similarly, while IQ is recognized as essential for effective decisions, its mediating role between GAI and EDM has not been sufficiently theorized or tested. This theoretical gap underscores the need to examine how GAI-driven improvements in information quality can enhance decision-making effectiveness, particularly in complex, project-based environments such as construction.

2.3 Empirical Literature

2.3.1 Generative AI and Decision -Making in Construction

Empirical studies on AI in construction primarily emphasize predictive analytics and automation, with limited attention to generative models. For instance, Zhang et al. (2022) and Lin et al. (2021) confirmed that AI supports project planning and cost estimation, but did not distinguish between traditional and generative AI. Miller et al. (2023) observed that AI-based reporting improved collaboration but did not assess its influence on strategic decision-making. Although evidence suggests that AI enhances efficiency and risk forecasting, empirical analysis of GAI's role in strategic and creative decisions remains scarce. This absence of context-specific research underscores the need to examine how GAI specifically improves decision-making in construction management.

2.3.2 Information Quality as a Mediator

Information Quality frequently serves as a mediating construct in technology–performance relationships across industries. Chen et al. (2020) found that AI-driven improvements in data quality enhanced managerial decision-making in finance, while Singh and Prasad (2021) reported similar findings in healthcare. In construction, Love et al. (2019) identified that real-time, accurate information significantly reduces project risks and cost deviations. However, no studies have yet empirically tested IQ as a mediator between Generative AI and Effective Decision-Making in construction. Understanding this mediation is crucial because GAI's contribution may be indirect, improving decision outcomes primarily through enhanced data accuracy, completeness, and timeliness.

2.3.3 Effective Decision -Making Outcomes

Empirical research consistently links high-quality information and analytical tools with better project outcomes, including reduced uncertainty and increased efficiency (Ali et al., 2018; Turner & Townsend, 2020). However, these studies focus on conventional decision-support tools rather than GAI-based systems. The absence of evidence linking GAI to specific decision outcomes, such as timeliness, accuracy, and risk reduction, represents a critical empirical gap. Investigating this link can clarify how GAI technologies directly influence decision-making effectiveness and project performance.

2.3.4 Empirical Gap

Most existing studies originate from developed economies and concentrate on traditional AI techniques. The distinct role of Generative AI in transforming decision-making processes, especially in developing contexts like Sri Lanka, remains underexplored. Furthermore, the mediating role of Information Quality between GAI and decision outcomes has not been empirically validated. These gaps limit understanding of how emerging technologies reshape managerial behavior in construction. Hence, this study seeks to address these empirical gaps by examining the interplay among GAI, IQ, and EDM in Sri Lanka's construction sector.

2.4 Conceptualization of the Research Model

Building on theoretical insights and empirical evidence, this study proposes a conceptual framework linking GAI, Information Quality, and Effective Decision-Making in the Sri Lankan construction industry.

2.4.1 Independent Variable -Generative Artificial Intelligence (GAI)

Encompasses three dimensions: Predictive Analytics, Automation in Data Processing, and Design and Planning Optimization—which collectively enhance data analysis, operational efficiency, and project planning (Goodfellow et al., 2014; RIBA, 2023).

2.4.2 Mediator -Information Quality (IQ)

Represents the attributes of accuracy, completeness, timeliness, and relevance that determine the reliability of data for managerial use (Wang & Strong, 1996). GAI is posited to enhance these attributes, thereby indirectly improving the effectiveness of decision-making (Chen et al., 2020; Love et al., 2019).

2.4.3 Dependent Variable -Effective Decision-Making (EDM)

Refers to decisions that are timely, accurate, and resource-efficient, leading to improved project outcomes and reduced risks (Simon, 1977; Ali et al., 2018).

2.4.4 Conceptual Framework

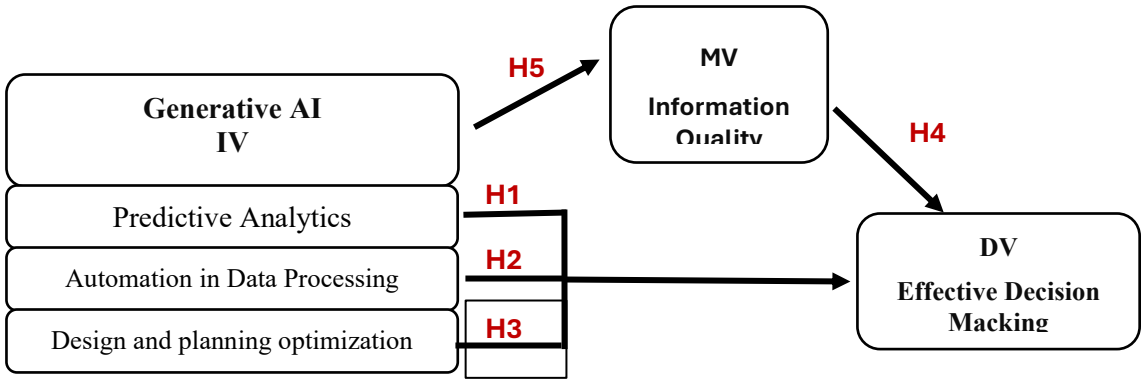


Fig. 1

2.4.5 Hypothesis

H1-Predictive Analysis has a significant positive impact on Information Quality in the construction industry in Sri Lanka.

H2-Automation of Data Processing has a significant positive impact on Information Quality in the construction industry in Sri Lanka.

H3-Design and Planning Optimization has a significant positive impact on Information Quality in the construction industry in Sri Lanka.

H4-Information Quality has a significant positive impact on Effective Decision-Making in the construction industry in Sri Lanka.

H5-Information Quality significantly mediates the relationship between GAI and Effective Decision-Making in the construction industry in Sri Lanka.

3. Methodology

3.1 Introduction

This chapter outlines the research methodology adopted to investigate the impact of Generative AI (GAI) on effective decision-making (EDM) in the Sri Lankan construction industry, with a focus on the mediating role of Information

Quality (IQ). It details the research design, population, sampling strategy, data collection methods, instrumentation, and analytical techniques. The chapter also addresses measures of validity and reliability, as well as ethical considerations, ensuring transparency, replicability, and rigor in the research process.

3.2 Study Design

3.2.1 Research Philosophy

The study follows a positivist research philosophy, emphasizing objectivity and empirical measurement. Positivism assumes an observable, measurable reality, enabling research to test hypotheses statistically and produce generalizable findings. This philosophy is well-suited to examining cause-and-effect relationships among GAI, IQ, and EDM.

3.2.2 Research Approach

A deductive approach is adopted, starting from existing theories and the conceptual framework to formulate hypotheses. Quantitative data are collected to test relationships among GAI dimensions (Predictive Analytics, Automation of Data Processing, Design and Planning Optimization), IQ, and EDM, ensuring a structured, objective analysis.

3.2.3 Methodological Choice

A mono-method quantitative design is employed, using structured questionnaires to collect numerical data. This approach aligns with the positivist philosophy and enables statistical hypothesis testing in large samples, ensuring objectivity and replicability.

3.2.4 Research Strategy

The study uses a survey strategy to gather data from construction professionals. Surveys are ideal for standardized, measurable data collection and allow statistical analysis of relationships between variables.

3.2.5 Time Horizon

A cross-sectional time horizon is applied, collecting data at a single point in time. This snapshot approach is efficient for testing hypothesized relationships without long-term tracking, aligning with the survey strategy and quantitative design.

3.3 Population, Sample & Sampling Technique

The target population comprises approximately 10,000–15,000 construction professionals in Sri Lanka who hold decision-making roles. The sample size was 384 respondents, calculated using Krejcie and Morgan's table to ensure a 95% confidence level. Purposive sampling, supplemented by snowball sampling, was employed to select participants with relevant experience in GAI and organizational decision-making.

3.4 Operationalization of Variables

Variables are operationalized using measurable indicators and a 5-point Likert scale for the GAI Components: Predictive Analytics, Automation, and Design & Planning Optimization. IQ: Accuracy, timeliness, completeness, relevance, clarity. EDM: Timeliness, accuracy, risk reduction, resource optimization.

3.5 Data Collection

A structured questionnaire was developed from validated scales. Data were collected online through email, WhatsApp, and professional networks. The survey included demographic questions and Likert-scale items covering GAI dimensions, IQ, and EDM. Validity was ensured through expert review and factor analysis; reliability was assessed using Cronbach's Alpha ($\alpha \geq 0.7$).

3.6 Data Presentation & Analysis

Data will be presented using descriptive statistics (means, standard deviations, frequencies). Inferential analysis includes correlation, regression, and mediation testing (Baron & Kenny method or SEM) using SPSS. This approach enables hypothesis testing and evaluation of the relationships among GAI, IQ, and EDM.

4. Data Presentation and Analysis

4.1 Introduction

This chapter presents the empirical results of a study examining how GAI influences Effective Decision-Making (EDM) in Sri Lanka's construction industry, with an emphasis on the mediating effect of Information Quality (IQ). Analyses include sample characteristics, data preparation, descriptive statistics, and inferential tests, as well as reliability, validity, correlation, regression, and mediation, to evaluate the proposed hypotheses.

4.2 Description of the Sample

The study analyzed data from 384 construction professionals representing various roles.

Table 4.1 Frequency table of respondents' job titles.

Job Title	Frequency	Percentage (%)
Project Manager	69	18%
Engineer	70	18%
Quantity Surveyor	81	21%
Site Supervisor	47	12%
IT Professional	41	11%
Administrative Officer	33	9%
Other	43	11%
Total	**384**	**100%**

As shown in Table 4.1, Quantity Surveyors constituted the largest group (21%), followed by Engineers (18%) and Project Managers (18%). The distribution ensures coverage across managerial, technical, and administrative functions, as shown in the table of respondents' Experience in the Construction Industry.

Years of Experience	Frequency	Percentage (%)
Less than 1 year	51	13%
1-3 Years	126	33%
4-6 Years	96	25%
7-10 Years	83	22%
Over 10 Years	28	7%
Total	**384**	100%

Regarding experience (Table 4.2), most respondents had 1- 3 years (33%) or 4–6 years (25%) of industry experience, indicating that the majority were early- to mid-career professionals familiar with emerging technologies.

Table 4.3 Frequency table of respondents' company adaptation of GAI.

Adaptation GAI	Frequency	Percentage (%)
Yes - fully integrated into processes	08	2%
Yes - partially adopted in some departments	159	41%
No - but currently exploring options	209	54%
No - no plans to adopt	08	2%
Total	**384**	100%

GAI adoption (Table 4.3) remains limited: 54% of firms are exploring options, 41% have partially adopted GAI, and only 2% have fully integrated it. These figures highlight growing interest but modest implementation across the sector.

4.3 Data Preparation

The dataset was fully complete (384 valid cases) with no missing values or extreme outliers. Skewness and kurtosis within ±2 confirmed approximate normality. Variables were coded under three constructs: GAI (Predictive Analytics, Automation, and Optimization), IQ, and EDM, allowing organized and consistent analysis.

4.4 Descriptive Analysis

Table 4.4 Descriptive Statistics of Main Constructs

Descriptive Statistics

	N	Minimum	Maximum	Mean	Std. Deviation	Skewness	
	Statistic	Statistic	Statistic	Statistic	Statistic	Statistic	Std. Error
EDM	384	3.00	5.00	4.2990	.28431	-.496	.125
GAI	384	3.17	5.00	4.3566	.28745	-.498	.125
Valid N (listwise)	384						

	Kurtosis	
	Statistic	Std. Error
EDM	2.605	.248

GAI	.535	.248
Valid N (listwise)		

The mean values of GAI (M=4.35) and EDM (M=4.29) indicate that respondents generally agreed with the positive influence of Generative AI on decision-making. Low standard deviations show consistency across responses. Negative skewness suggests that most responses leaned toward higher agreement, reinforcing the notion that GAI is widely perceived as beneficial.

4.5 Inferential Analysis

4.5.1 Reliability

Table 4.5 Cronbach's Alpha Values for Constructs.

Construct	Cronbach's alpha	No. Of items	Reliability level
Predictive analysis (GAIP)	0.647	4	Acceptable
Automation of data processing (GAIA)	0.710	4	Good
Optimization (GAIO)	0.623	4	Acceptable
Information quality (IQ)	0.605	5	Acceptable

Cronbach's Alpha values demonstrated acceptable internal consistency: Predictive Analytics = 0.647, Automation = 0.710, Optimization = 0.623, and IQ = 0.605. All exceed the exploratory threshold (0.60), confirming the reliability of the measurement scales.

4.5.2 Validity (Factor Analysis)

Table 4.6 KMO and Bartlett's Test

Kaiser-Meyer-Olkin Measure of Sampling Adequacy.		.906
Bartlett's Test of Sphericity	Approx. Chi-Square	2787.708
	df	231
	Sig.	<.001

The Kaiser-Meyer-Olkin = 0.906 and Bartlett's Test $p < 0.001$ indicated sampling adequacy and significant inter-item correlations. Four extracted components accounted for 52.2% of the total variance, verifying construct validity and confirming the instrument's suitability.

4.5.3 Correlation

Table 4.7 Correlation between GAI and EDM

		EDM	GAI
EDM	Pearson Correlation	1	.742**
	Sig. (2-tailed)		<.001
	N	384	384
GAI	Pearson Correlation	.742**	1
	Sig. (2-tailed)	<.001	
	N	384	384

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

A strong, positive, and significant relationship was found between GAI and EDM ($r = 0.742$, $p < 0.01$). This suggests that greater GAI integration is associated with more effective and timely decision-making in construction operations.

4.5.4 Regression

The regression model ($R^2 = 0.562$, $p < 0.001$) explains 56% of the variance in EDM. All GAI dimensions significantly influence EDM: Optimization ($\beta = 0.380$) – the strongest predictor; Predictive Analytics ($\beta = 0.295$); and Automation ($\beta = 0.241$). The results show that design and planning optimization yields the greatest improvements in decision-making, while the Durbin-Watson statistic of 1.871 indicates no autocorrelation.

4.5.5 Mediation

Mediation testing (PROCESS Macro) confirmed that IQ partially mediates the relationship between GAI and EDM.

Path a (GAI → IQ): B = 0.828, $p < 0.001$, Path b (IQ → EDM | GAI): B = 0.273, $p < 0.001$, Total effect = 0.734; Direct effect = 0.508, Indirect effect = 0.226 (Sobel $z = 5.446$, $p < 0.001$) The bootstrap CI [0.124, 0.333] confirmed statistical significance. Thus, GAI enhances decision-making both directly and indirectly by improving the accuracy, timeliness, and relevance of information.

4.6 Hypotheses Testing

Table 4.11 Summary of Hypotheses Testing.

ANOVA[a]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	17.406	3	5.802	162.679	<.001[b]
	Residual	13.553	380	.036		
	Total	30.960	383			

a. Dependent Variable: EDM

b. Predictors: (Constant), GAIO, GAIA, GAIP

ANOVA results ($F = 162.679$, $p < 0.001$) validate the overall model significance. These findings empirically confirm that the three GAI dimensions enhance decision-making effectiveness primarily through improved information quality.

5 Conclusion and Recommendations

5.1 Introduction

This chapter concludes the study on the impact of Generative Artificial Intelligence (GAI) on Effective Decision-Making (EDM) in Sri Lanka's construction industry, emphasizing the mediating role of Information Quality (IQ). It synthesizes the findings, interprets their implications, and proposes recommendations for construction stakeholders, policymakers, and researchers to enhance digital transformation and data-driven decision-making.

5.2 Summary of Findings

Based on data from 384 construction professionals, the study confirmed that GAI significantly enhances decision-making effectiveness by improving information quality. Regression analysis showed all three GAI dimensions, Predictive Analytics, Automation of Data Processing, and Design and Planning Optimization, positively influence EDM, with Design and Planning Optimization having the strongest impact. Information quality (accuracy, timeliness, relevance, and understandability) partially mediated the GAI–EDM relationship. The findings suggest that GAI adoption can address key industry inefficiencies, including project delays, cost overruns, and poor resource utilization, by enabling evidence-based, data-driven managerial decisions.

5.3 Conclusion and Recommendations

The study concludes that GAI serves as a transformative enabler of effective decision-making in construction, primarily by improving the quality of information available to professionals. Recommendations for Construction Companies: Integrate GAI tools into project management systems to automate, enable predictive analytics, and optimize design, while investing in workforce training. For Policymakers: Formulate national frameworks and incentives to promote AI adoption, ensuring standardization and accessibility. For Technology Providers: Develop localized, user-friendly AI platforms suited to Sri Lanka's construction environment. For Industry Professionals: Engage in continuous professional development to strengthen digital literacy and AI competency.

5.4 Implications of the Study

Theoretically, this research contributes to the limited literature on GAI applications in developing countries and validates the mediating role of information quality in decision-making. In practice, it provides actionable insights for firms seeking to enhance productivity and competitive advantage through digital transformation. The results underscore that high-quality information is essential for maximizing the value of AI-generated insights, while policy frameworks are needed to foster sector-wide adoption.

5.5 Limitations and Future Research

The study's scope was limited to the Sri Lankan construction sector and three GAI dimensions, using cross-sectional data. Future research should adopt longitudinal and comparative approaches, explore emerging AI applications, and examine organizational and cultural factors influencing adoption.

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Second International Conference on Circular Economy and Sustainable Ecosystem 2025