Towards a Socio-Techno-Ecological Framework (RESCUE) for Smart Waste Management for Urban Areas in Sri Lanka: A Conceptual Model

V.P.M. Vitharana
Department of Electrical and Computer Engineering
The Open University of Sri Lanka
Nawala, Nugegoda, Sri Lanka
vpmvitharana@gmail.com

P.S.A.M. Fernando
Department of Electrical and Computer Engineering
The Open University of Sri Lanka
Nawala, Nugegoda, Sri Lanka
sachinayon@gmail.com

S.V.S. Rukshitha
Department of Electrical and Computer Engineering
The Open University of Sri Lanka
Nawala, Nugegoda, Sri Lanka
sumithur98@gmail.com

K.D. Nethmini
Department of Electrical and Computer Engineering
The Open University of Sri Lanka
Nawala, Nugegoda, Sri Lanka
nethminidinithi1@gmail.com

N.P.M.S. Dharmasena
Department of Electrical and Computer Engineering
The Open University of Sri Lanka
Nawala, Nugegoda, Sri Lanka
punsarani2001@gmail.com

B.M.G.S.T.S.K. Wickramasinghe
Department of Electrical and Computer Engineering
The Open University of Sri Lanka
Nawala, Nugegoda, Sri Lanka
bmwic@ou.ac.lk

***Abstract*— Urbanization in Sri Lanka is accelerating rapidly, with nearly 47% of the population projected to live in urban centers by 2035, up from 19% in 2000. This surge, coupled with rising consumerism, has intensified municipal solid waste (MSW) challenges, particularly in cities like Colombo, which generates over 1,200 tons of waste daily. Current waste management practices remain linear, collection, disposal, and landfill, leading to weak recycling rates, poor infrastructure, and limited citizen engagement, thereby worsening plastic pollution, biodiversity loss, and climate-linked disasters. This study proposes RESCUE (Real-time Environmental Surveillance and Community-Utilized Ecology), a novel socio-techno-ecological framework tailored for Sri Lankan urban contexts. The study employed a conceptual systems design approach integrating a comprehensive literature review, stakeholder mapping, cultural profiling, ecological assessment, and iterative framework modelling. RESCUE integrates AI-driven predictive analytics, IoT-enabled infrastructure, community engagement, and ecological risk profiling to deliver an adaptive, inclusive, and resilient urban waste management system. The framework comprises four interconnected layers: data infrastructure, analytics and decision-making, community engagement, and governance feedback. Comparative analysis with global systems, such as those in Barcelona, Seoul, Singapore, and INSEE's Ecocycle, demonstrates RESCUE's novelty in embedding social inclusivity, ecological sensitivity, and technological integration. Pilot deployments, multi-stakeholder collaborations, and real-time monitoring strategies are recommended for validation. This framework aligns with UN Sustainable Development Goals (SDGs), particularly SDG 11 (Sustainable Cities) and SDG 12 (Responsible Consumption). RESCUE offers a scalable, replicable model for urban waste governance in Sri Lanka and other rapidly urbanizing South Asian cities.**

Keywords: AI-driven analytics, RESCUE framework, smart cities, sustainability, urban waste governance

I. Introduction

Sri Lanka faces an unprecedented urbanization rate, with nearly 47% of its population projected to live in cities by 2035 [1]. This rapid growth, paired with shifting consumption patterns, has caused a surge in municipal solid waste (MSW) generation. For example, Colombo alone produces over 1,200 tonnes of waste per day, much of which remains unsorted and improperly disposed of [2]. These challenges manifest as clogged waterways, increased plastic pollution, biodiversity loss, and climate-induced vulnerabilities such as floods and landslides [3], [19].

Existing waste management models in Sri Lanka remain predominantly linear, collection, disposal, and landfill, with minimal recycling, weak infrastructure, and low community participation [4], [20]. Imported smart waste management (SWM) solutions using IoT, AI, and GIS have shown global promise but fail to account for local socio-cultural and ecological dynamics, resulting in ineffective implementations.

This calls for a contextualized, hybrid system, one that fosters technological efficiency, cultural inclusivity, and environmental resilience. Introducing RESCUE, Real-time Environmental Surveillance and Community-Utilized Ecology, a socio-techno-ecological framework integrating AI-driven operations, IoT infrastructure, and citizen engagement adapted for Sri Lankan urban landscapes.

RESCUE aligns with UN Sustainable Development Goals, especially SDG 11 (Sustainable Cities) and SDG 12 (Responsible Consumption), by marrying smart infrastructure with community-led waste behaviors and ecological risk forecasting [7]. Its novelty lies in blending predictive analytics, cultural-network dynamics, and environmental-risk profiling for a layered, adaptive system.

As the baseline of the study, the main objectives were laid,

1. To design a socio-techno-ecological framework for sustainable urban waste management in Sri Lanka.
2. To integrate AI-driven analytics, IoT infrastructure, community engagement, and ecological profiling into a unified framework.
3. To evaluate how the proposed framework addresses gaps in technology adoption, social inclusivity, and environmental resilience.

II. Literature Review

A. Global Smart Waste Endeavors

Cities worldwide are pioneering SWM with IoT-infused bins and AI-enhanced logistics. In Barcelona, smart sensors across bins enable real-time monitoring to cut operational costs by 20% [8]. Seoul's RFID-enabled "pay-as-you-throw" pricing system changes household behavior by linking waste volume to cost [9]. Singapore's pneumatic waste conveyance systems reduce manual touchpoints in dense housing [10].

B. The Role of AI and Predictive Systems

AI offers tools for route optimization, image-based waste sorting, and waste generation forecasting tied to demographic and event-based variables [11], [12]. Computer vision techniques have boosted recycling accuracy in trials across Europe and Japan [13].

C. Sri Lankan Ground Realities and Gaps

Despite external advances, Sri Lankan cities face limitations. CEA's efforts in digital waste collection reporting remain under-adopted due to low awareness [15]. Cultural stigma toward waste collection persists [16]. Local pilot projects, like IoT bins in Colombo [4] and AI-based CCTV waste monitoring in Galle's Moda Ela canal, illustrate potential but are not scalable [0]. Community-led models have succeeded, e.g., women-run material recovery centers in Puttalam, blending gender equity with recycling [5]. And projects like UN Women's involvement in Puttalam and Mannar mobilize women for waste governance, improving social cohesion [2], [3].

Initiatives like INSEE's Ecocycle Resource Recovery Centre demonstrate resource circularity in Sri Lanka, recovering value from FMCG waste at scale [6]. Yet, these efforts lack integration with social or eco-risk components.

D. Integrating Socio-Techno-Ecological Insights

Literature underscores that SWM must go beyond technology to integrate community dynamics and environmental planning [17], [18]. South Asia's informal waste economies, built on local-level trust and labor networks, can be harnessed ethically and sustainably [19]. Yet, a unified framework that blends real-time analytics, ecological risk modeling, and cultural empowerment is still missing.

III. Methodology

This paper leverages conceptual systems design, anchored in literature review, stakeholder mapping, and systems thinking, to craft the RESCUE framework.

A. Framework Development Process

The situational analysis begins by identifying the critical failures in current waste management systems, particularly within Sri Lankan urban contexts. These include mounting environmental pressure on landfills due to inadequate waste segregation, inefficient collection schedules, and improper disposal practices. Social disengagement also plays a significant role, as public participation in waste reduction and recycling remains limited, often hindered by low awareness and a lack of accessible facilities. Technological gaps, such as the absence of real-time monitoring systems and data-driven decision-making tools, further exacerbate these challenges, leaving municipalities reactive rather than proactive.

The RESCUE framework development process is as follows (Figure 1).

- Situational Analysis - Identified inefficiencies in waste segregation, collection schedules, and landfill pressures
- Technology Feasibility Assessment - Evaluated AI, IoT, and GIS tools for adaptability and cost-effectiveness
- Cultural Mapping - Assessed social levers, including the roles of religious institutions, women-led MRFs, and educational outreach
- Ecological Assessment - Mapped flood-prone areas, biodiversity corridors, and marine pollution hotspots
- Layered Framework Design - Developed a modular structure for scalability and adaptability

From a technological feasibility standpoint, the study assesses the maturity, accessibility, and affordability of emerging tools such as Internet of Things (IoT) sensors, artificial intelligence (AI)-driven analytics, and Geographic Information System (GIS) mapping. These technologies are evaluated for their adaptability to the socio-economic realities of Sri Lankan communities, ensuring that any proposed system remains cost-effective and scalable. The analysis also considers how these technologies can be integrated with existing infrastructure without imposing prohibitive costs or requiring highly specialized skills.

Cultural mapping is then incorporated to ensure that the proposed smart waste management system aligns with local social structures and values. This involves identifying and leveraging influential social levers, such as the active role of religious institutions in community mobilization, the leadership potential of women in household waste management, and the capacity of education systems to instil sustainable practices in younger generations. By integrating these elements, the system gains cultural legitimacy and a higher likelihood of adoption.

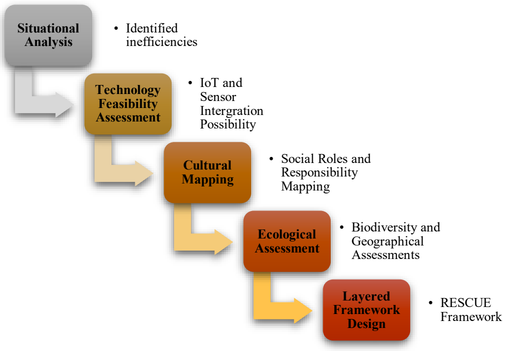

Figure 2: RESCUE Framework Development Process

The ecological assessment maps critical environmental parameters, including flood-prone areas, coastal zones vulnerable to waste leakage, and biodiversity corridors that require protection from pollution. This spatial analysis ensures that waste management strategies are ecologically sensitive and aligned with broader climate adaptation and biodiversity conservation goals.

In addition, the layered framework design outlines a modular, interactive structure for implementation, allowing for both vertical and horizontal scalability. This approach facilitates phased adoption, starting with pilot zones, while enabling integration of additional modules such as AI-based waste sorting, community participation dashboards, and predictive maintenance for waste infrastructure. The framework is intentionally adaptable, accommodating future technological advancements and evolving policy landscapes, thus ensuring long-term sustainability and resilience.

B. RESCUE Framework Components

The RESCUE framework consists of four active layers (Figure 2).

1. Data Infrastructure Layer - IoT bins, environmental sensors, citizen reporting portals
2. Analytics Layer - Machine learning models for forecasting, routing optimization, and ecological risk prediction
3. Community Engagement Layer - Gamified apps, women-led facilities, school-based composting
4. Governance Layer - Dashboards, transparency protocols, and adaptive policy refinement

The data infrastructure layer forms the foundational backbone of the proposed smart waste management system, integrating multiple data sources to ensure comprehensive monitoring and control. This includes IoT-enabled smart bins capable of tracking fill levels and waste types, CCTV systems designed to detect and analyze litter flow patterns, and citizen-reporting portals that empower the public to log incidents of illegal dumping or missed collections. Real-time environmental sensors further enhance the system by capturing air quality, temperature, and other indicators that may correlate with waste decomposition rates or public health risks. Together, these tools create a robust, continuous stream of actionable data.

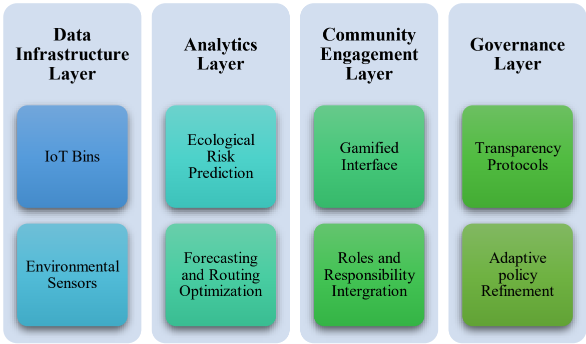

Figure 1: RESCUE Framework Architecture

Building on this foundation, the analytical and decision layer leverages advanced machine learning models to translate raw data into actionable intelligence. These models can forecast waste surges based on historical patterns, seasonal events, and demographic changes, enabling proactive resource allocation. They also optimize route planning for collection vehicles, reducing fuel consumption and operational costs, while anomaly detection algorithms flag instances of illegal dumping or equipment malfunction. Additionally, the system integrates ecological risk factors, such as flood alerts, to calibrate waste handling protocols, ensuring that waste is managed efficiently and without exacerbating environmental vulnerabilities.

The community engagement layer focuses on cultivating long-term behavioral change and fostering public ownership of the system. This includes gamified mobile applications that encourage proper waste segregation and recycling through point-based rewards, women-led material recovery facilities (MRFs) that empower local female entrepreneurs, and school-led composting programs that embed sustainability principles into education. These initiatives are carefully tailored to align with established community trust pathways, ensuring acceptance and sustained participation.

Furthermore, the governance and feedback layer ensures transparency and accountability through interactive dashboards that display system performance metrics, environmental impact data, and citizen feedback. Policymakers can use these insights to refine strategies, allocate resources more effectively, and maintain public trust. This layer also closes the loop by feeding community input back into the decision-making process, creating a dynamic, responsive governance model that adapts to both environmental and social changes over time.

C. *Implementation Roadmap*

The pilot rollout phase focuses on deploying the RESCUE framework across a variety of urban wards that reflect Sri Lanka's diverse environmental and social contexts. For example, Colombo's flood-prone wards present complex challenges of waste accumulation during heavy rains, Kandy's densely populated residential zones struggle with waste overflow and collection inefficiencies, while Galle's coastal areas face marine pollution risks linked to improper waste disposal. Selecting such varied pilot sites allows the framework to be stress-tested against multiple urban realities, ensuring adaptability and effectiveness.

Table 1 highlights how RESCUE addresses gaps in existing Sri Lankan SWM approaches.

Table 1: Current Smart Waste Management vs. RESCUE

Dimension	**Current Challenge**	**RESCUE Contribution**
Technology	Low real-time monitoring	AI + IoT integration
Social	Weak citizen engagement	Gamified participation + women-led MRFs
Ecology	Neglected flood/biodiversity risks	Embedded ecological profiling
Governance	Policy fragmentation	Data-driven adaptive governance

Following deployment, data calibration and AI training become essential steps. Operational data from waste collection, environmental sensor readings, and behavioral inputs from community engagement tools are continuously gathered to refine the system's predictive capabilities. This iterative process improves machine learning models that forecast waste surges, detect anomalies, and optimize routing while adapting to local behavioral patterns and ecological conditions.

To ensure sustainability and broader impact, the framework emphasizes policy alignment and the formation of public-private partnerships (PPPs). Municipal agencies coordinate with private recyclers, NGOs such as UN Women and INSEE, and technology providers to share responsibilities and resources. These collaborations enhance governance capacity, mobilize community resources, and foster innovation by combining the strengths of different sectors within an inclusive governance model.

Moreover, the framework's socio-ecological scaling strategy expands implementation beyond pilot areas through iterative feedback loops. These loops incorporate community reporting mechanisms, ecological monitoring data, and incentive programs that encourage sustainable practices. By continuously integrating feedback from citizens and adapting to changing environmental conditions, the system evolves into a resilient, community-centric urban waste management solution capable of scaling city-wide and eventually nationwide.

IV. Discussion

The RESCUE model introduces three key innovations that distinguish it from conventional smart waste management approaches. First, it incorporates embedded socio-ecological intelligence by integrating cultural drivers and environmental thresholds into its design. This approach acknowledges the critical role of community-led waste centers, which not only foster social unity but also generate economic resources, as demonstrated by successful initiatives in Puttalam [5] and Dehiwala [1]. Second, the model employs predictive, ecologically layered operations that move beyond the limitations of linear, reactive waste systems. Utilizing AI, RESCUE forecasts significant events, such as waste surges during the Vesak festival or monsoon-induced flooding, enabling proactive route adjustments and targeted public awareness campaigns. Finally, RESCUE is designed with modular scalability and inclusivity in mind, allowing incremental adoption based on local capacities. Areas with limited infrastructure can begin with community engagement and material recovery centers, while wards equipped with advanced resources can implement full IoT and AI integration. Furthermore, gamified applications incentivize recycling behavior through tokenized rewards, a system that can be further enhanced by emerging blockchain technologies aligned with Extended Producer Responsibility policies [10]. This layered flexibility ensures that RESCUE remains adaptable, accessible, and effective across diverse urban contexts.

A. *Risks & Barriers*

Implementing the RESCUE framework faces several challenges, beginning with infrastructure costs, as IoT sensors and AI systems require significant capital investment. However, these costs can be mitigated through public-private partnerships (PPPs) and a modular rollout approach that allows gradual scaling based on available resources. Ensuring digital literacy and equitable access is another critical concern; the system must incorporate multilingual applications, SMS integration, and analog fallback options to engage diverse user groups effectively and inclusively. Data privacy is addressed through transparency measures embedded within the governance layer, including data anonymization techniques that protect citizen information while maintaining system accountability. Lastly, overcoming stakeholder fragmentation necessitates the cultivation of cross-sector dialogues, policy alignment, and the development of co-owned digital platforms that foster collaboration among municipal authorities, private sector partners, community organizations, and technology providers.

B. Comparative Frameworks

While Barcelona's smart waste management system primarily emphasizes operational efficiency through the deployment of sensor-equipped smart bins, and INSEE's resource recovery center concentrates on maximizing recycling throughput and material reclamation, the RESCUE framework uniquely integrates both these technological and operational strengths. Beyond mere efficiency, RESCUE incorporates layers of social empowerment by actively engaging communities in waste management processes, thereby fostering behavioral change and inclusive participation. At the same time, it embeds ecological foresight by accounting for environmental vulnerabilities such as flood-prone areas and biodiversity corridors. This multifaceted integration transforms the approach into a holistic urban resilience engine, capable of adapting to social dynamics and ecological constraints while maintaining high operational standards.

RESCUE's novelty lies in its multi-layered integration of technological intelligence, social inclusivity, and ecological sensitivity. Comparative evaluation shows:

- Barcelona focuses on operational efficiency.
- INSEE emphasizes resource recovery but lacks scalability.
- RESCUE combines both while embedding predictive risk modeling and community-driven governance.

V. Conclusions and Recommendations

RESCUE offers a layered, adaptive architecture for smart waste management tailored to Sri Lanka's urban challenges. It blends cutting-edge technology with grassroots mobilization and ecological resilience.

To effectively implement the RESCUE framework, several key recommendations are proposed. Firstly, pilot microsystems should be deployed across diverse municipal wards to test and validate the socio-technological assumptions of the model in real-world settings. Secondly, robust citizen engagement programs must be developed, incorporating elements such as gamified mobile applications to encourage participation, women-led waste collectives to empower local communities, and educational curricula focused on waste management in schools to cultivate sustainable habits from a young age. Thirdly, ecological monitoring capabilities should be enhanced by integrating real-time flood and pollution sensors into the waste management operations, ensuring environmental risks are addressed proactively. Fourthly, policy frameworks need to be established that reward community participation, incentivize recycling behaviors, and promote data sharing across municipal councils to enable coordinated and transparent governance. Finally, longitudinal studies should be conducted to systematically measure the environmental benefits, such as reductions in landfill use and improvements in biodiversity, alongside social engagement outcomes and economic efficiency, thereby providing evidence-based insights to guide continuous improvement and scaling.

Future research should validate RESCUE through:

- Pilot testing in Colombo and Kandy.
- Quantitative KPIs: reduced landfill use, improved recycling rates.
- Citizen behavior analysis and ecological resilience metrics.

If effectively implemented, RESCUE could become a signature model for integrated, sustainable, and context-sensitive urban waste governance, one that other South Asian cities could adapt for resilient futures.

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