Transforming E-waste into Opportunity: Smart Management and Recycling Solutions for Sustainable Growth in Bangladesh

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Abstract

Introduction

Waste management is a pressing challenge in Bangladesh due to rapid urbanization, industrial growth, and insufficient infrastructure. Existing systems struggle to manage increasing waste volumes, leading to environmental degradation and public health concerns. The need for sustainable solutions aligned with circular economy principles is critical for addressing these challenges.

Objective

This study aims to investigate current waste management practices in Bangladesh, identify systemic gaps, and propose sustainable and innovative solutions. The research seeks to answer how smart technologies and circular economy strategies can optimize resource recovery, reduce environmental impact, and contribute to economic growth.

Methodology

A mixed-methods approach was adopted, combining a scoping review based on the PRISMA framework and secondary data analysis. Over 500 sources were screened, and 45 peer-reviewed studies were selected for detailed review. Quantitative data from government reports, academic studies, and environmental assessments were analyzed. Additionally, a conceptual smart waste management framework was developed, incorporating technologies such as the Internet of Things (IoT) and Artificial Intelligence (AI).

Results
Findings reveal significant inefficiencies in Bangladesh's waste management systems, including dependency on informal practices and weak policy enforcement. Waste-to-energy (WtE) technologies, organic composting, and improved recycling infrastructure present high-impact opportunities for economic and environmental benefits. Smart technologies can optimize waste collection, sorting, and resource recovery processes.

Conclusions
The study concludes that integrating smart waste management technologies and circular economy strategies can address the systemic gaps in Bangladesh's waste management. Effective policy reforms, public-private partnerships, and community engagement are essential to ensure sustainable outcomes.

Implication of the Study
This research contributes a comprehensive framework for sustainable waste management in Bangladesh and similar developing countries. By leveraging advanced technologies and fostering collaborations, the study highlights how waste can be transformed into economic opportunities, reducing environmental risks and promoting long-term sustainability.

Keywords: Waste Management, Sustainable Solutions, Artificial Intelligence, Environmental Impact

1. Introduction

The rapid growth of the electronics sector and the increasing demand for technology have triggered an unparalleled rise in electronic waste (e-waste), creating significant environmental, health, and economic challenges. E-waste, which refers to discarded electrical and electronic devices, has become the fastest-growing waste category worldwide (Riyad et al., 2014). Globally, e-waste production has reached 57.4 million metric tons (MMT) annually, with Asia contributing the largest share of 24.9 MMT (Roy et al., 2022). In developing countries like Bangladesh, where infrastructure for e-waste management is inadequate, the situation is critical. This surge in e-waste is causing harmful effects on both human health and the environment.

In Bangladesh, e-waste originates from both local usage and imported waste, especially from the ship-breaking industry. As of 2021, approximately 0.6 MMT of e-waste was generated locally, with another 2.5 MMT contributed by the ship-breaking sector (Roy et al., 2022). Informal recycling practices dominate the e-waste sector, with around 120,000 individuals in Dhaka alone—50,000 of whom are children—engaged in unsafe e-waste handling and recycling operations. These practices expose workers to toxic heavy metals such as lead, copper, and nickel, resulting in severe health risks and environmental degradation (Mowla et al., 2021).

Despite the introduction of the **Hazardous Waste (E-Waste) Management Act** in 2021, weak enforcement and a lack of public awareness hinder its effectiveness. As a result, e-waste continues to accumulate without proper management. However, there are considerable economic

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opportunities in this sector. Globally, the raw materials in e-waste are valued at approximately $57 billion, but only $10 billion worth is recycled sustainably (Osborne, 2024). In Bangladesh, the recovery of metals from printed circuit boards could generate up to $1 billion annually by 2030 (Roy et al., 2022).

Conceptual Model:

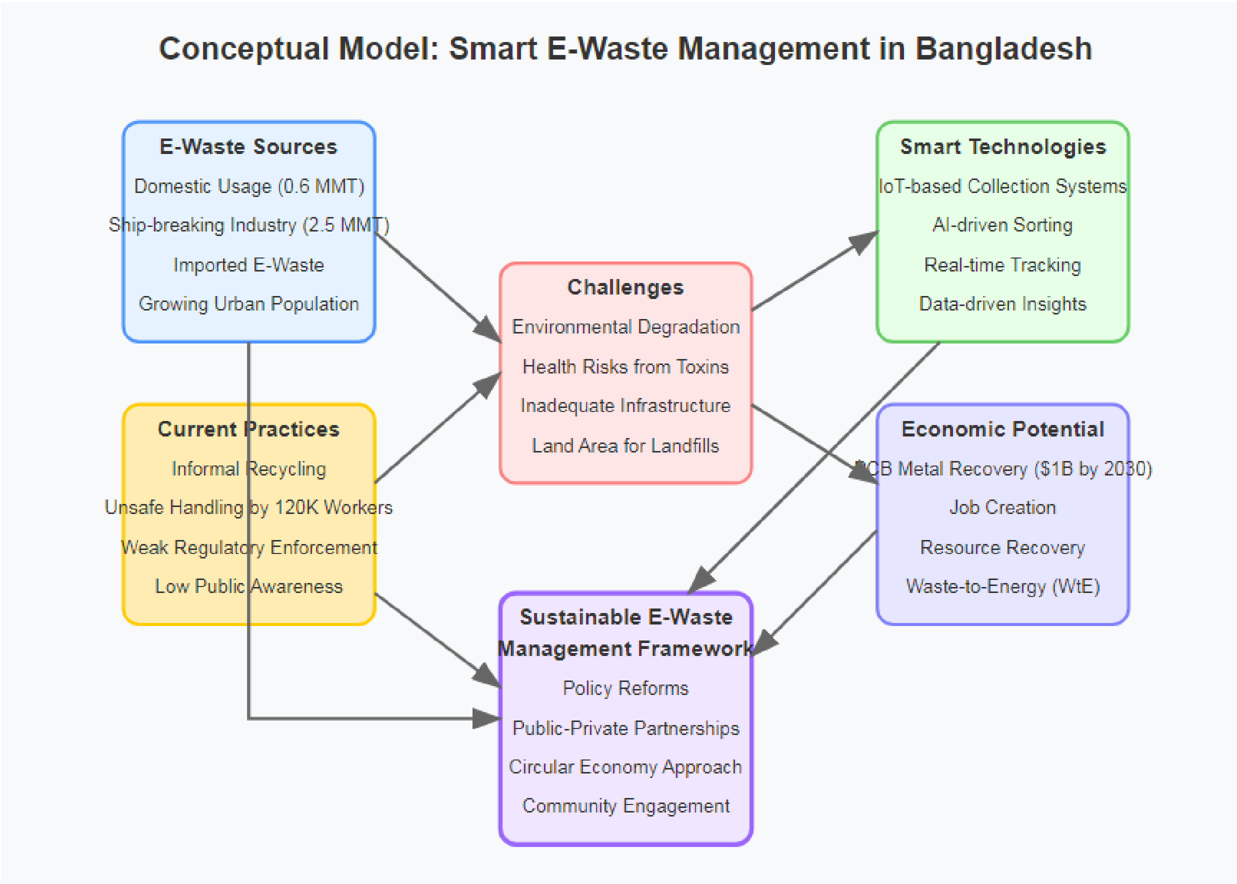

Figure-1. Conceptual Model

This conceptual model illustrates a framework for Smart E-Waste Management in Bangladesh. It's organized into six interconnected components:

1. **E-Waste Sources**: Identifies major contributors including domestic usage (0.6 MMT), ship-breaking industry (2.5 MMT), imported e-waste, and waste from growing urban populations.
2. **Current Practices**: Highlights problematic approaches including informal recycling, unsafe handling by approximately 120K workers, weak regulatory enforcement, and low public awareness.
3. **Challenges**: Outlines key issues such as environmental degradation, health risks from toxins, inadequate infrastructure, and limited land area for landfills.

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4. **Smart Technologies**: Proposes solutions including IoT-based collection systems, AI-driven sorting, real-time tracking, and data-driven insights.
5. **Economic Potential**: Emphasizes opportunities like precious metal recovery (projected $1B by 2030), job creation, resource recovery, and waste-to-energy conversion.
6. **Sustainable E-Waste Management Framework**: Presents strategic approaches including policy reforms, public-private partnerships, circular economy approaches, and community engagement.

The model uses arrows to show relationships between these components, illustrating how sources and current practices contribute to challenges, which in turn drive the need for both smart technologies and a sustainable management framework, ultimately leading to economic benefits.

Problem Statement

The lack of an organized e-waste management system in Bangladesh, coupled with informal recycling practices and weak regulatory enforcement, has created a critical situation. Without immediate intervention, the health, environmental, and economic risks posed by unmanaged e-waste will continue to escalate. The challenge lies in transitioning from informal, hazardous practices to a sustainable e-waste management framework that balances environmental protection with economic benefits.

Hypotheses

1. **H1:** Effective e-waste management can reduce environmental pollution and improve public health in Bangladesh.
2. **H2:** Integrating technology-driven solutions and policy reforms can unlock significant economic potential in e-waste management.

Research Questions

1. What are the current practices and challenges in e-waste management in Bangladesh?
2. How does informal e-waste recycling impact health and the environment?
3. What sustainable solutions, including policy reforms and technological innovations, can be proposed to improve e-waste management in Bangladesh?

2. Literature review

E-waste management highlights the global economic, environmental, and health issues linked to improper disposal of electronic devices, with a particular focus on developing countries like Bangladesh. This section reviews existing studies on e-waste management practices, challenges, and opportunities, emphasizing sustainable and eco-friendly solution.

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2.1 Growth and composition of e-waste

The global increase in electronic device usage has resulted in record levels of e-waste. By 2021, global e-waste generation was estimated at 57.4 million metric tons (MMT) annually, with Asia accounting for the largest share at 24.9 MMT (Roy et al., 2022). In Bangladesh, e-waste comes from both domestic consumption (0.6 MMT) and imports, particularly from ship-breaking yards, which contribute an additional 2.5 MMT to the country's waste (Roy et al., 2022). However, the lack of updated data since 2022 may not accurately reflect the current situation. E-waste contains hazardous substances like lead, cadmium, and mercury, which pose serious risks when improperly managed. Research shows that these pollutants can cause significant soil and water contamination if not properly recycled or disposed of (Mowla et al., 2021).

2.2 Economic potential of e-waste recycling

Dhaka, one of the most densely populated cities in the world, has a population of around 20 million within just 360 km² (UN-Habitat, 2022). The city's population is growing rapidly at a rate of 1.4% annually, with the urban population increasing even faster at 3.4% per year (World Bank, 2020). By 2040, Dhaka's population is expected to reach 40 million (BBS, 2021). This rapid population growth directly contributes to increasing waste generation, including e-waste. In 1985, the city's total solid waste amounted to 1,040 tons per day, rising to 3,500 tons per day by 1999 and projected to reach 30,000 tons per day by 2020 (JICA, 2017). Although Dhaka generates large amounts of municipal solid waste, with 80% of it being organic and containing 50-70% moisture, only about 50% is properly collected by the Dhaka City Corporation (DCC) and disposed of in landfills (Hoornweg&Bhada-Tata, 2012). This situation underscores the growing challenge of managing e-waste alongside the overall increase in waste, exacerbated by the city's rapid population growth.

Improper waste management has resulted in a significant accumulation of uncollected waste, creating serious environmental hazards in the Dhaka City Corporation's (DCC) North and South zones. Although the corporations have been implementing new initiatives to address the issue, the problem continues to worsen daily. The scale of the waste issue appears to be beyond the DCC's capacity to manage alone, highlighting the need for city residents to actively participate and contribute to a collective solution.

As the amount of waste grows, the area required for landfilling is also increasing. It is estimated that by 2020, the land area needed for landfills would range from 206.31 acres to 309.46 acres(World Bank, 2012). Traditionally, waste has been seen as "an unwanted material that has no financial value, regardless of time or season, because there is no market demand for it" (UNEP, 2016). However, this view can be challenged through effective reuse and recycling. Globally, various Waste-to-Energy (WtE) technologies have been developed to convert unwanted waste into valuable energy (Hoornweg&Bhada-Tata, 2012). Additionally, waste can be decomposed to produce fertilizers, supporting sustainable agricultural practices. Rather than being a burden, Dhaka's waste could be transformed into a valuable resource, offering significant benefits to the city's residents if modern technologies are effectively implemented (JICA, 2017).

Despite the challenges, e-waste offers significant economic opportunities. According to Osborne (2024), the total raw material value of global e-waste is estimated at around $57 billion, with only $10 billion being recycled sustainably. This presents a considerable economic potential, particularly for developing countries like Bangladesh. In Bangladesh, efficient metal recovery from discarded electronics, such as printed circuit boards (PCBs), could generate up to $1 billion annually by 2030 (Roy et al., 2022). Realizing this potential requires substantial investment in technology and infrastructure to support safe and efficient recycling practices, underscoring the need for a shift towards a more organized and sustainable e-waste management system.

A thorough review of the current waste management situation and its challenges has become essential in order to find a potential solution, while also transforming this vast amount of waste into valuable resources.

Electronic waste (e-waste) has become a growing global concern due to its rapid increase and the challenges associated with its proper disposal and recycling. Understanding e-waste generation, recycling trends, and economic opportunities in recycling is crucial for developing effective waste management strategies. The following analysis explores key aspects of e-waste management through three figures: the rising trend of e-waste generation and recycling, a comparison of formal and informal recycling practices across different regions, and the economic potential of recycling valuable e-waste components. These insights highlight the widening gap between e-waste production and recycling, the role of informal recycling in certain regions, and the financial benefits of improved recycling systems.

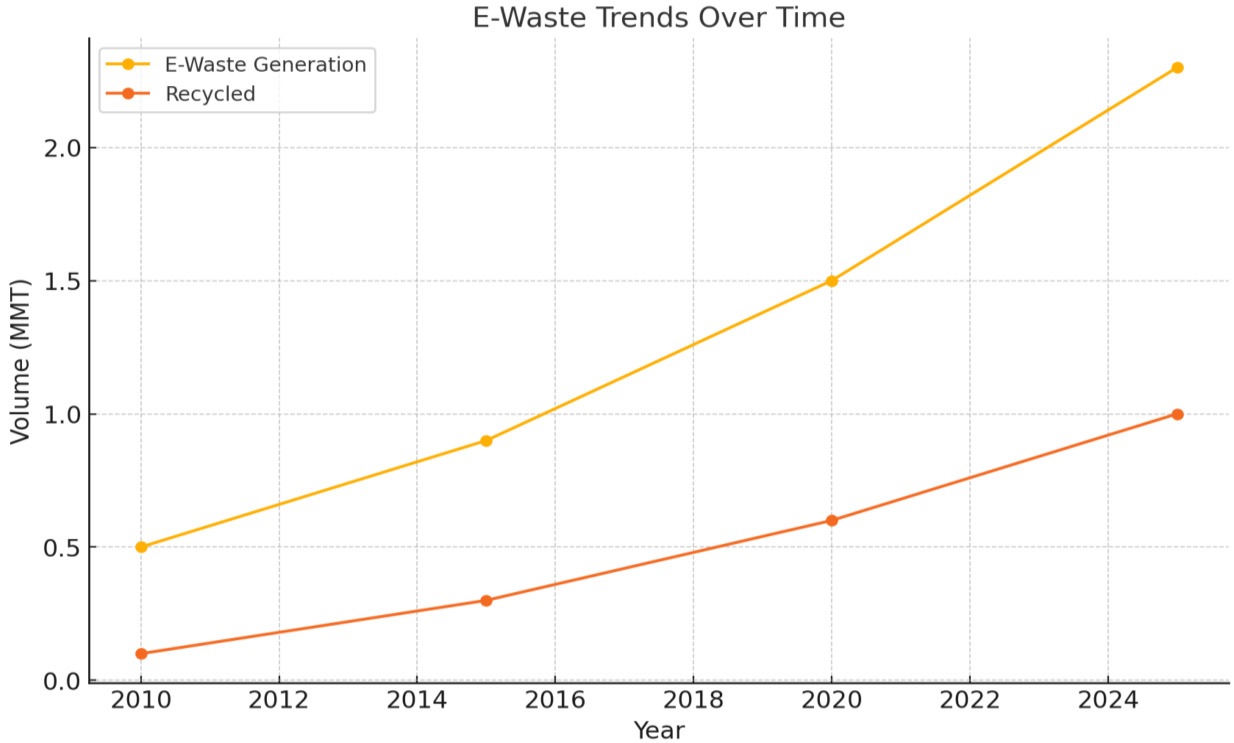

Figure-2. E-waste trends over Time

Roy et al. (2022) and global e-waste monitoring reports

"E-Waste Trends Over Time" shows the volume of **E-Waste Generation** and **Recycling** from 2010 to 2025 in **million metric tons (MMT)**. The **yellow line** represents **E-Waste Generation**, which shows a steady increase over time, reaching over **2.0 MMT by 2025**. The **orange line** represents **Recycling**, which also increases but at a much slower rate, remaining significantly lower than total generation. This indicates a growing gap between e-waste production and recycling efforts.

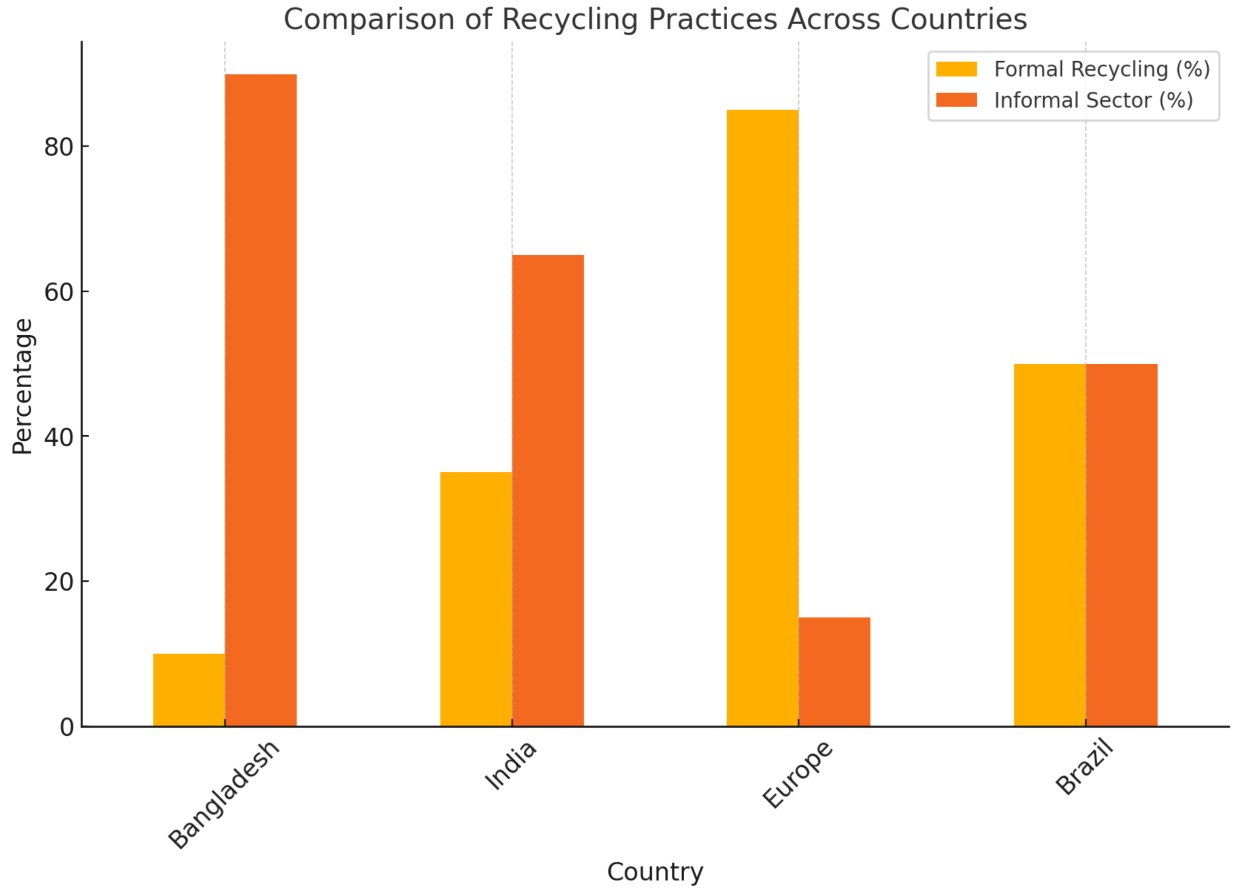

Figure -3. Comparison of recycling practices across countries

This bar chart compares **formal** and **informal** e-waste recycling practices in four regions: **Bangladesh, India, Europe, and Brazil**. The **yellow bars** represent **formal recycling**, while the **orange bars** represent the **informal sector**. Bangladesh and India rely heavily on the informal sector, whereas Europe has a high percentage of formal recycling. Brazil shows a balanced split between both sectors.

E-Waste Management Rules (2016), the WEEE Directive in Europe, and informal sector integration in Brazil. Specific data were adapted from Mowla et al. (2021) and Rahman (2017).

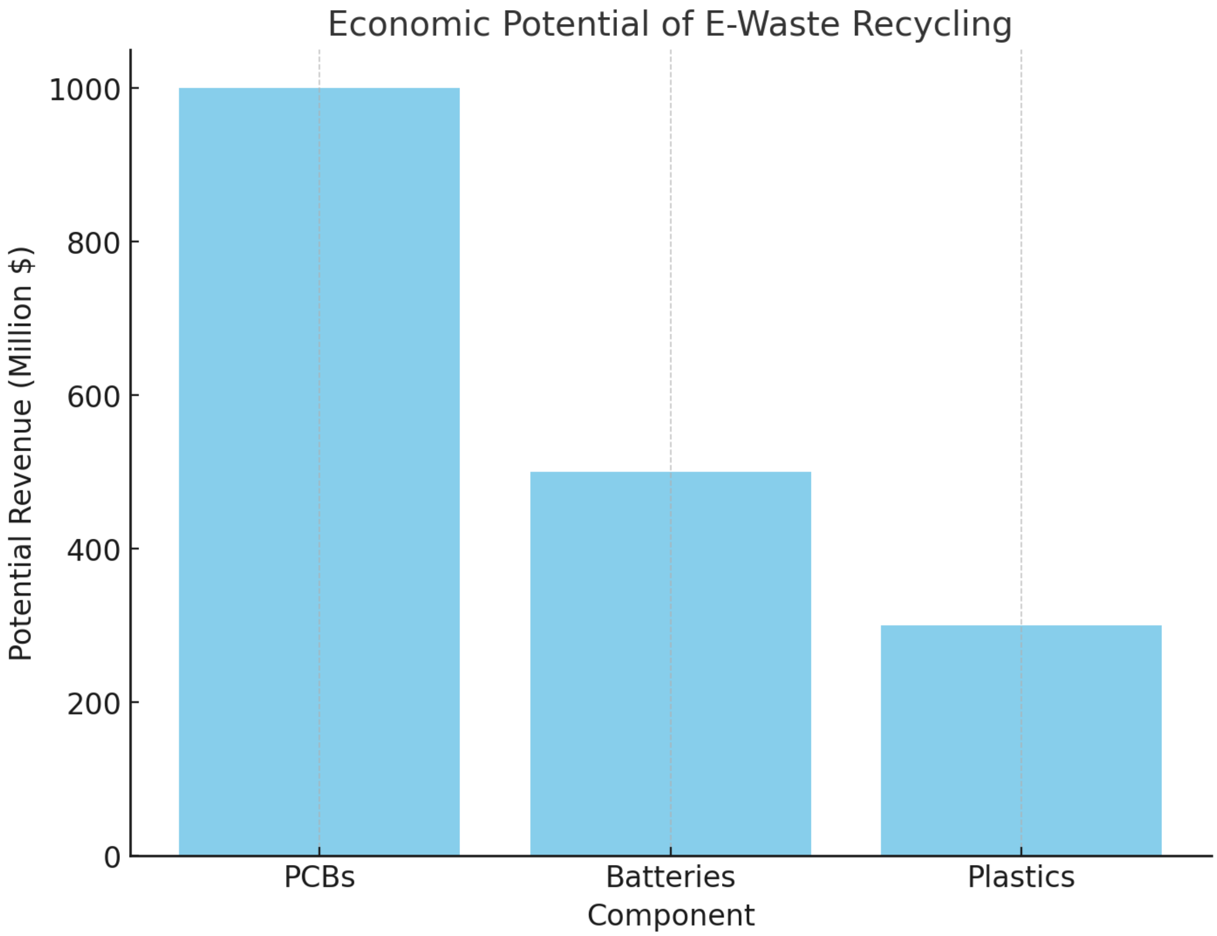

Figure-4. Economic potential of e-waste recycling

This bar chart highlights the **potential revenue** from recycling different e-waste components. **Printed Circuit Boards (PCBs)** have the highest revenue potential, exceeding **$1 billion**, followed by **batteries** and **plastics**, which generate lower but still significant economic returns. This emphasizes the financial benefits of effective e-waste recycling. The financial figures for recycling components like printed circuit boards (PCBs) and batteries were estimated from findings in Roy et al. (2022)

Figure 1 presents a line chart that demonstrates the rising trend in e-waste generation and recycling volumes in Bangladesh, emphasizing the gap between total e-waste and the amount that is actually recycled. Figure 2 features a bar chart that compares the percentage of formal and informal recycling practices across Bangladesh, India, Europe, and Brazil, offering insights into global recycling trends and potential areas for improvement. Meanwhile, Figure 3 displays a bar chart illustrating the economic potential of recycling critical components such as printed circuit boards (PCBs), batteries, and plastics, underscoring the financial advantages of effective e-waste management.

2.3 Technological innovations in smart e-waste management framework

The integration of smart technologies presents promising solutions to the challenges of e-waste management. Das et al. (2022) highlight the potential of IoT and AI-driven waste management systems to optimize e-waste collection, sorting, and recycling processes (Olawade et al., 2024). These technologies offer real-time tracking, efficient waste material classification, and data-driven insights that can significantly improve the efficiency of recycling operations. By adopting such technologies, it is possible to reduce costs, increase resource recovery rates, and minimize environmental impact. However, the high initial investment required and the limited technological infrastructure in Bangladesh pose significant barriers to the widespread adoption of these advanced solutions. Roy et al. (2022) propose a business model (see Figure 4) focused on metal recovery from e-waste, particularly from printed circuit boards, which could generate significant revenue while also reducing environmental harm. This model not only promotes resource recovery but also supports job creation and economic development. The circular economy approach, aligned with sustainable development goals, represents a shift towards long-term, environmentally-friendly waste management practice.

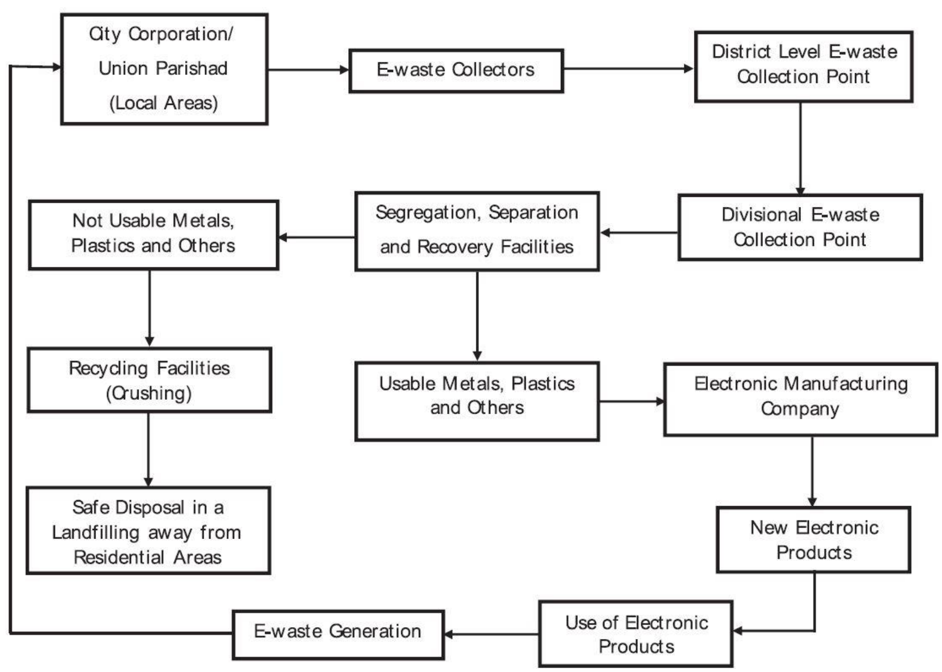

Figure -5: Proposed model for sustainable e-waste management.

Roy et al (2022)

Roy et al. (2022) also acknowledge that the current study has several limitations, meaning the actual situation may differ from the findings. Specifically, e-waste generation and metal recovery are likely to be higher than the estimated values. Nonetheless, the study provides a reasonable projection for future e-waste-based business models, highlighting that Bangladesh has significant potential to capitalize on e-waste as a resource. The Government of Bangladesh (GoB) should

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invest in developing recovery infrastructure and encourage private-sector recyclers to engage in formal e-waste recycling businesses.

The literature review highlights that although e-waste management in Bangladesh faces considerable challenges, it also offers economic opportunities if addressed through effective policies, public awareness, and technological innovations. Research consistently emphasizes the importance of a well-structured regulatory framework, public education campaigns, and investment in smart waste management technologies. By shifting towards formal recycling practices, fostering public involvement, and implementing innovative solutions, Bangladesh can achieve sustainable and cost-effective e-waste management, ultimately safeguarding public health and the environment.

2.4 Theoretical perspectives

Theoretical approaches to e-waste management focus on sustainability models, the role of the informal economy, and technological advancements. Sustainable development theories, like the circular economy, offer a basis for understanding how recovering resources from e-waste can reduce environmental harm while promoting economic growth (Roy et al., 2022). This model highlights the importance of reducing waste, encouraging reuse and recycling, and lowering the environmental impact of disposed electronics.

The informal recycling sector in Bangladesh, characterized by manual dismantling and hazardous practices, underscores the importance of socio-economic theories that focus on informal economies. These theories shed light on how informal networks flourish when regulatory frameworks are weak and formal economic options are limited, often at the expense of health and safety (Mowla et al., 2021). Tackling this issue necessitates policy interventions that prioritize social equity and health protectio.

Technological frameworks, including the use of IoT and AI in waste management, are underpinned by theories of smart infrastructure and data-driven decision-making. These technologies promote efficiency and transparency in resource management, facilitating optimized processes for waste collection, sorting, and recycling (Das et al., 2022). The smart e-waste management framework proposed by Roy et al. (2022, Figure 4) integrates these innovations, presenting a conceptual model that incorporates user-oriented features such as real-time tracking and compliance monitoring.

Additionally, public awareness and behavior change models, like the Theory of Planned Behavior (TPB) (Ajzen, 2020), offer valuable insights into how individuals and communities can be encouraged to adopt responsible e-waste disposal practices. These models highlight the role of attitudes, perceived behavioral control, and social norms in influencing environmentally sustainable behaviors.

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3. Method

This study uses a mixed-methods approach, combining a scoping review with additional primary data collection, to investigate the implementation of smart e-waste management systems (Khan et al., 2023) in Bangladesh. The methodology aims to thoroughly address the study's objectives (Sosunova, 2023), which involve quantifying e-waste generation, evaluating its environmental and health impacts, and proposing a smart, cost-effective, and eco-friendly e-waste management system.

The scoping review approach was chosen to identify publications focused on the application of smart waste management systems. This method was selected intentionally, as it offers more flexibility than a systematic review, enabling researchers to adapt the literature and key study terms (Thomas et al., 2020; Sabiston et al., 2022).

The search for relevant material included platforms such as Scopus, selected for its extensive access to nearly all peer-reviewed publications across various research fields (Pranckutė, 2021). Essential search terms were used to identify relevant articles for the investigation. Table 1 presents a schematic overview of the methodology used to select the literature for this study. The review process resulted in the identification of 45 relevant publications. It is important to note that all the selected articles are published works from developing nations, including regions such as Bangladesh, India, Gambia, Kenya, Nigeria, and Brazil. A summary of the most relevant articles, which contribute to issues similar to this study, is provided in Table 2.

This study primarily collects data from various secondary sources, as they are considered more reliable for describing trends and listing innovations (Ponta et al., 2021). Government reports were used to gather statistics on e-waste generation and management. The Scopus database provided access to academic literature and research papers on e-waste management practices, while various environmental reports were consulted to understand e-waste disposal methods.

Table- 1. Review procedure of the current investigation

SPAR-4-SLR (PRISMA)	Consideration	Decision
Assembling (Identification)	Search focus	e-waste management and recycling
	Search keywords	(e-waste AND management AND recycling)
	Search database	Scopus
	Search field	Article title, abstract, and keywords
	Search result	565 documents
Arranging (Screening and Eligibility)	Search period	2015 until 2025
	Subject area	“Environmental Science, Engineering, Energy, Social Sciences, Business, Management and Accounting”, “Economics, Agricultural and Biological Sciences” 254
	Document type	“Article” 215
	Publication stage	“Final”150
	Source type	“Journal”100
	Language	“English” 45
	Search result	**45 ocuments**

4. Results

4.1 Result and Discussion

The study’s key findings are systematically organized under specific headings corresponding to the research questions introduced at the outset. Table 3 presents the results from the analysis of various use cases, focusing on the integration of e-waste management systems in different contexts. **In Section 4.1**, the existing waste management system of Dhaka City Corporation (DCC) is examined, considering typical features of landfill sites in Dhaka, along with data on the city’s population, waste generation, and waste volume (Table 3 and Table 4) to determine the density of disposal in each area. **Section 4.2** discusses the DCC Solid Waste Management system, highlighting the commonly used composting systems in Bangladesh. Finally, Section 4.3 outlines the main challenges involved in implementing smart waste and e-waste management systems in Bangladesh.

Table- 2. Review of the articles

Authors & Years	Title of the paper	Objective of the study	Findings of the study
Mohammed &Kaida, (2024)	Opportunities and challenges for circular economy in the Maldives: A stakeholder analysis of informal E-waste management in the Greater Mal´e Region	To examine the current and anticipated scenarios of e-waste management in the Greater Malé Region of the Maldives. To explore the role of the informal sector in e-waste management and the potential for its formalization. To identify opportunities and challenges for advancing the circular economy in the Maldives' e-waste sector.	Formalizing the informal sector can encourage greater consumer engagement and increase resource recovery. The informal sector significantly contributes to managing e-waste, but government support is needed to enhance safety and productivity. Opportunities include an active informal workforce and rising e-waste generation, while challenges involve stereotypes against informal workers and inadequate government support.
Tasnim et al., (2024)	Influence of Canadian provincial stewardship model attributes on the cost effectiveness of e-waste management	This study aimed to analyze e-waste collection and management trends across six Canadian provinces from 2013 to 2020, focusing on collection rates, stewardship model attributes, and budget allocations. It also sought to examine the impact of geographical collaboration among provinces and explore the potential benefits of an integrated e-waste management approach.	The study revealed that stewardship model attributes significantly influence e-waste collection rates, with Quebec showing a 61.5% surge in collection. A positive correlation was found between e-waste collection rates and the growth of businesses and collection sites in Western Canada, highlighting the advantages of collaboration. Findings also indicate that cost efficiency improves with higher e-waste volumes managed per steward, though some provinces allocated minimal budgets for transfer and storage.
Kumar et al., (2024)	E-Waste Sustainability via Institutional-Recycler	This study aimed to explore the potential of fostering cooperation between recycling	The study emphasized the importance of inclusive initiatives involving manufacturers, consumers,

	Collaboration: Creating an Electronics Circular Economy	centers and institutions to develop a sustainable circular economy for e-waste. It reviewed literature and case studies to identify the benefits and challenges of such collaboration and highlighted critical factors like regulatory incentives, public awareness, and innovation to promote systemic change in e-waste management.	policymakers, and civil society to foster accountability across the product lifecycle. Successful global cooperation models were analyzed, showcasing their adaptability and limitations. Practical recommendations were provided for stakeholders to reduce e-waste's environmental impact, unlock economic opportunities, and drive sustainable development through collaboration.
Sari et al., (2024)	Economic and Environmental Benefits of E-Waste Management Networks Design in Yogyakarta Province, Indonesia	The growing consumption of electronic devices, particularly smartphones, has led to a significant rise in e-waste, but effective management systems remain lacking. This study seeks to design a collaborative network integrating formal and informal channels for e-waste management, aiming to optimize economic and environmental benefits across the supply chain.	The proposed e-waste management network, integrating formal and informal channels, offers substantial supply chain benefits. With a 10,000 IDR incentive, it encourages consumer and informal collector participation, generating a monthly profit of 5.529×10^{10} IDR from Yogyakarta Province. While formal channels provide higher returns than informal ones, they require significant investment and are viable only if at least 33% of total supply is directed to them, alongside an intangible profit contribution of 3.4%.
JosephNg et al., (2024)	Managing Sustainable E-Waste Resilient Infrastructure with Smart Bin	This study aims to explore the environmental challenges posed by rising e-waste due to the growing demand for electronic goods globally. It examines	The study found that the surge in e-waste, with Malaysia producing 365,000 tones annually, demands urgent action. Initiatives like ERTH's collection services significantly reduce e-waste's environmental impact, highlighting the

		sustainable e-waste management practices, highlighting innovative solutions like ERTH's collection services in Malaysia, and emphasizes the need for stakeholder engagement in promoting responsible disposal and recycling.	importance of innovative practices and stakeholder collaboration in fostering a sustainable and eco-friendly approach to electronic consumption.
Wang &Anand, (2024)	Creative Design-Driven Interdisciplinary Studio Course for Electronic Waste Management	This paper aims to emphasize the need for interdisciplinary, design-driven studio education to raise awareness about electronic waste among students from diverse academic backgrounds. It seeks to highlight the importance of teaching recycling, reuse, and responsible disposal of e-waste while fostering creative problem-solving and collaboration between departments to develop inclusive courses.	The study found that existing e-waste courses predominantly target engineering students, leaving a gap for interdisciplinary approaches. Design-driven studios can encourage practical learning by integrating creativity with reusing e-waste components, promoting sustainable habits among students. Collaboration between departments is essential to make e-waste education accessible and impactful for all academic disciplines.
Kombe&Shemsanga, (2024)	Sustainability and economic potential of solid waste generated in Tanzania's largest university campus	This study aimed to analyze the sources, composition, and volume of solid waste generated at the University of Dodoma in Tanzania, and to evaluate its environmental and economic potential. It sought to identify opportunities for recycling, composting,	The study revealed that the university generates an average of 644.56 tonnes of solid waste annually, with 90.76% being recyclable, valued at $142,301.20 USD, and 9.24% compostable. Despite this potential, waste sorting and separation are absent. Recycling and composting could enhance sustainability and profitability, offering valuable lessons for universities

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		and biogas generation, providing recommendations for sustainable waste management on campus.	aiming to implement effective waste management practices.
Hsu et al.,(2024)	E-Waste: A Global Problem, Its Impacts, and Solutions	This article aims to provide an overview of the critical considerations surrounding the e-waste crisis, including managerial, environmental, labor, and health perspectives. It seeks to identify the factors and challenges affecting e-waste management globally and proposes strategies, solutions, and future research directions.	The study highlights significant variability in the effectiveness and availability of e-waste management approaches worldwide. It underscores the need for a comprehensive global framework to address the challenges, offering actionable strategies and recommendations for sustainable e-waste management and areas for further research.
Apprey et al., (2024)	Sustainable Practices in E-Waste Management: A Study of Electronic Repair Technicians in Ho Municipality, Ghana	This study aimed to investigate e-waste management and recycling practices among electronic service technicians in Ghana's Ho municipality, focusing on their awareness of environmental impacts, government regulations, and effective recycling strategies. It sought to identify gaps and propose policy measures to enhance sustainable e-waste practices aligned with the Sustainable Development Goals (SDGs).	The study revealed significant gaps in knowledge about e-waste disposal laws and hazardous materials among technicians, with qualifications influencing awareness levels. Common practices included storage and sale to scrap dealers, while 52% favored a nominal fee-based recycling approach. The findings stress the need for targeted awareness campaigns through GESTA platforms and local authorities to reshape perceptions and improve e-waste management practices.

Munni et al., (2024)	Awareness, Safety Practices and Associated Factors Among E-Waste Recycling Workers in Bangladesh	This study aimed to assess the awareness, safety measures, and factors influencing e-waste workers' practices in Bangladesh. It sought to identify knowledge gaps and the relationship between awareness and safety behaviors, in order to recommend interventions to improve workers' safety and environmental health in the e-waste sector.	The study found that only 25% of workers had good awareness of e-waste, with major gaps in understanding health hazards and environmental impacts. While 58% of workers followed good safety practices, the use of protective gear was inadequate. Factors such as higher education, training, and work experience were significantly associated with better awareness and safety practices. The study highlights the need for urgent interventions, including training and policy enforcement, to improve awareness and safety in the sector.
Jaiswal&Mukti, (2024).	E-waste circularity in India: identifying and overcoming key barriers	This article aims to identify the key barriers affecting the implementation of a circular economy for e-waste management in India. It seeks to analyze these barriers using expert opinions from industry and academia, along with previous literature, to provide insights into the challenges hindering effective e-waste recycling in the country.	The study identified major barriers to the circular economy of e-waste in India, including lack of incentives, insufficient customer awareness about the circular economy, and inadequate government policies. The analysis, using interpretive structural modeling (ISM) and fuzzy MICMAC techniques, highlights these factors as critical challenges that need to be addressed to promote sustainable e-waste management practices in India.
Sakhre et al., (2024)	Inventory and management of E-waste: a case study of Kerala, India	This study aims to quantify the electronic waste (E-waste) inventory in Kerala and develop a comprehensive	The study forecasts a substantial rise in E-waste in Kerala, with the highest generation projected for 2028–2029, estimated at 97,541 tonnes. The proposed

		management plan to address the environmental challenges posed by the increasing E-waste generation. It focuses on estimating E-waste based on sales data and "end-of-life" durations of electronic equipment, while proposing a 3R-based (reduce, reuse, recycle) strategy for efficient management.	management plan includes the establishment of 78 collection units and 273 recycling units statewide, focusing on strategic locations like Malappuram. This plan emphasizes effective E-waste collection, segregation, and recycling, offering a "cradle-to-grave" framework for sustainable E-waste management at various levels.

4.2 Existing waste management of Dhaka city corporation

The Dhaka City Corporation (DCC) is primarily responsible for waste collection and management in Dhaka, Bangladesh (Saqib, 2018). Despite the limited scope of waste management services in the city, the door-to-door, community-based waste collection system from households to local bins has been considered a success. Informal waste recycling systems have also proven effective, contributing significantly to waste recycling and creating jobs for the poor.

Waste is typically collected in a non-segregated manner and placed in small containers at households. It is then collected by DCC-designated organizations using vans and transported to secondary collection points. Waste trucks subsequently carry the waste to landfill sites. A large portion of the solid waste is processed by the informal sector for recycling. Scavengers, known as Tokais, collect recyclable items from landfills and open dustbins and sell them to waste recycling dealers (Bhangari). Additionally, hawkers purchase recyclables door-to-door and sell them to the Bhangari. The recyclables are then washed, dried, sorted, and traded in the market by the recycling dealers.

The waste management process for city streets in Dhaka differs from household waste collection. Cleaners employed by the Dhaka City Corporation (DCC) regularly clean public spaces, such as drains, streets, and parks. All the waste collected from the city is then sent to landfill sites. However, a large portion of the waste in Dhaka remains uncollected due to limited funding, inadequate infrastructure, and a shortage of transportation vehicles. In addition to solid waste, the city also generates electronic waste, construction waste, medical waste, food waste, and various forms of industrial waste.

The DCC lacks the capacity to regulate and manage these diverse types of waste. Furthermore, there are no specific laws in place to govern the management of these wastes, resulting in their continuous mixing with solid waste. Dhaka City is divided into two main areas: DCC (North), which consists of 36 wards, and DCC (South), which has 56 wards. All the waste from Dhaka is transported for landfilling at the Matuail and Amin Bazar dumping grounds. Waste from 55 wards is dumped in Matuail, while waste from 36 wards is sent to Amin Bazar. In 2016-2017, the Dhaka North City Corporation (DNCC) transported 852,391 tons of waste to the landfill, a 24.77% increase from the previous year (2015-2016).

Table -3. Typical features of landfill sites in Dhaka City

Salient features	**Landfills of Dhaka**	
	Matuail	**Amin Bazar**
Area (hectares)	40	20
Condition	In operation	In operation
Landfilling Started	2003	2007
Height of MSW deposit	7 meter	6.4 meter
Distance from the city (km)	6	8
Closed/expected end of life	2021	2023
Average disposal per day	2000 tons	1200 tons
Current CH4 Status	No recovery	No recovery
Ward Covered	55	36

The Dhaka City Corporation (North) is projected to manage over 5,637,728 tons of waste over the next five years. The growth percentage of waste collection between 2015 and 2017, as well as the projected waste volume in DNCC from 2017-18 to 2021-22, is illustrated in the charts below. By 2050, the composting landfill requirement is expected to cover around 400 acres, while the landfill requirement without composting will exceed 1,000 acres.

The future landfill requirements for Dhaka, both with and without composting, are further detailed in the chart below. The demand for landfills to dispose of municipal solid waste (MSW) in Dhaka has been assessed by projecting population growth and waste generation from 2007 to 2025,Table 4.

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Table- 4: Population, waste generation and waste volume in Dhaka city (2007 – 2025); Source: Typical features of Landfill sites in Dhaka City; Source: Authors generated from the survey and DCC reports.

Year	Projected population	Daily waste Generation (tons)	Yearly waste generation (M tons)	Cumulative waste (M tons)	Cumulative landfill waste volume (Mm3)
2007	13.50	6750	2.5	2.5	4.93
2008	13.87	6934	2.5	5.0	9.99
2009	14.24	7122	2.6	7.6	15.19
2010	14.63	7316	2.7	10.3	20.53
2011	15.03	7515	2.7	13.0	26.01
2012	15.44	7719	2.8	15.8	31.65
2013	15.86	7929	2.9	18.7	37.44
2014	16.29	8145	3.0	21.7	43.38
2015	16.73	8367	3.1	24.7	49.49
2016	17.19	8594	3.1	27.9	55.77
2017	17.66	8828	3.2	31.1	62.21
2018	18.14	9068	3.3	34.4	68.83
2019	18.63	9315	3.4	37.8	75.63
2020	19.14	9568	3.5	41.3	82.61
2021	19.66	9828	3.6	44.9	89.79
2022	20.19	10096	3.7	48.6	97.16
2023	20.74	10370	3.8	52.4	104.73
2024	21.30	10652	3.9	56.3	112.50
2025	21.88	10952	4.0	60.9	120.49

4.3 Initiatives taken by DCC for solid waste management

In early 2016, around six thousand mini bins were installed at various points throughout Dhaka. These bins were intended for pedestrians to dispose of light garbage, preventing littering in public spaces. However, the bins were not widely used as expected, with pedestrians often

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choosing to throw waste on the streets or footpaths. Street vendors, on the other hand, do prefer to use the bins.

Two major initiatives have been implemented to improve solid waste management in Dhaka. The first, launched by the Japan International Cooperation Agency (JICA) in 2005, aimed to formulate a master plan for Dhaka City and enhance the management skills of the Dhaka City Corporation (DCC). The second, the 3R Strategy (Reduce, Reuse, Recycle), was introduced in 2010 by the Department of Environment (DoE) under the Ministry of Environment and Forestry of the Government of Bangladesh. The 3Rs play a crucial role in sustainable waste management, helping to protect the environment by reducing greenhouse gas emissions and converting waste into valuable resources.

The Department of Environment (DoE) has introduced a program that involves building two waste management plants in Dhaka, which will use solid waste collected from various parts of the city to produce compost fertilizer. One plant is located in Matuail under the Dhaka South City Corporation (DSCC), and the other is in Amin Bazar under the Dhaka North City Corporation (DNCC). Each plant is designed to produce 20 tons of compost fertilizer per day from solid waste. The DCC anticipated the production of fertilizer from these plants to begin by early 2018.

Another significant development in waste management in Dhaka has been the construction of Street Transfer Stations (STS). In DNCC, 52 STSs have been built, helping to reduce the number of waste containers on the roads. While 45 STSs were planned for DSCC, only 12 have been completed so far. DNCC plans to construct 2 to 4 additional STSs in each of its 36 wards. In the areas of primary waste collection, the Primary Waste Collection Service Provider (PWCSP), an NGO, coordinates the collection of waste from households to the STS. In 2016-2017, 340 private operators were registered with the PWCSP, though there are also unregistered operators involved in waste collection. The construction of STSs has helped resolve traffic bottlenecks caused by waste containers on the streets.

4.3.1. Smart Dumping and Transportation of Waste

In the current waste management system, dustbins are placed on the streets, and when they overflow, waste spills onto the road, leading to environmental pollution. Additionally, these dustbins occupy a significant portion of the street, obstructing traffic and contributing to traffic jams. Underground dust containers present an ideal solution to these issues.

In this system, similar to models in India, dustbins are placed underground as large bins, with only a narrow opening through which waste is deposited. This method keeps the waste below ground, significantly reducing the risk of pollution and street congestion. The process is outlined in a systematic order, as shown below:

Waste is collected from households or public places.The waste is transported to the underground dust container. The narrow opening allows for waste to be deposited without spilling over.The

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container is sealed underground, preventing waste from contaminating the street or causing pollution. The waste is periodically removed from the underground container using specialized equipment.

4.3.2. Energy Generation from the Waste

Waste-to-energy (WtE) refers to the process of converting waste into energy, such as electricity, heat, or transport fuels (Kumar &Samadder, 2017). WtE is recognized as one of the eight technologies with significant potential to contribute to a future low-carbon energy system, as noted in the World Economic Forum's 2009 report "Green Investing: Towards a Clean Energy Infrastructure" (Ayodele et al., 2017). Notably, the electrical energy generation potential from WtE has increased from 456,900 MWh in 1995 to an estimated 1,894,400 MWh by 2025. The electrical energy recovery from urban solid waste in Dhaka could supply a substantial portion of the city's energy consumption needs.

Several technologies can be used for converting waste into energy. Each WtE solution has unique characteristics and varying feasibility, depending on factors such as waste composition, technological infrastructure, and economic viability. Below is an overview of the available WtE technologies:

This process involves burning waste at high temperatures to generate heat, which is then converted into electricity or used for district heating. It is one of the most common WtE technologies worldwide. Organic waste is broken down by bacteria in the absence of oxygen, producing biogas (mainly methane), which can be used for electricity generation or as a fuel for transportation. Waste is heated in a low-oxygen environment to produce synthetic gas (syngas), which can be used to generate electricity or be converted into chemicals and fuels.

Similar to gasification but in the absence of oxygen, this process decomposes waste at high temperatures to produce oil, gas, and charcoal, which can be used for energy production. Landfill gas, primarily methane, is captured from landfills and used to generate electricity or heat. This process helps reduce greenhouse gas emissions from waste disposal sites.This technology uses a plasma arc to ionize waste material, creating a high-temperature environment that produces syngas and a vitrified slag byproduct. This is considered a more advanced method of waste conversion.

MBT involves sorting and biologically processing waste to recover recyclables and produce a waste fraction that can be used in energy generation, typically through combustion or anaerobic digestion. Organic waste is fermented to produce bioethanol or other biofuels. This method is often used for agricultural waste, food waste, and certain types of biodegradable materials.

Each of these technologies can be adapted based on local waste composition and energy needs, making WtE a versatile option for cities like Dhaka to address both waste management and energy generation challenges.

4.3.3. Fertilizer Generation from Waste:

Waste Concern states that if recyclable materials, including organic waste for composting, are properly separated, the total waste can be reduced by 60-70%. However, only 15% of the recyclable waste, collected by approximately 87,000 waste pickers, is being recovered, leaving a significant amount of organic waste behind. This organic waste could potentially be transformed into a large quantity of organic fertilizer. A survey conducted by Waste Concern in Dhaka and surrounding areas revealed that 94% of farmers are willing to purchase compost. Despite this, the yield is currently too low, and the organic matter in soil was found to be less than 1%, compared to the critical level of 3%.

Fertilizer can be produced through biological treatment processes like anaerobic digestion and composting. Anaerobic digestion has already been discussed. Several composting methods can be employed to generate organic manure from municipal solid waste. These methods include static pile composting, contained pile composting, vermi-composting, bin composting, windrow composting, rotary drum composting, tunnel composting, and in-vessel composting(Table 5). An overview of these composting procedures is summarized in:

Table-5. An overview of different commonly used composting systems

Criteria	**Static and containe d pile**	**Vermi**	**Bin**	**Windr ow**	**Rotator drum**	**Tunnel**	**In-vessel**
Size and form of the heap/ container	Waste is laid out in parallel rows; considera bly taller and wider rows can be had compared to windrows ; especiall y in contained pile systems	Can be done in pits, concrete tanks, well rings, or in wooden or plastic crates appropriat e to a given situation.	Bins of different sizes and materials are used	The waste is laid out in paralle l rows; 2–3 m high and 3–4 m wide across the base; acquir es trapez oidal shape.	Rotary drum with 3 m or larger diameter is used for pretreating the waste; the waste is then windrowed	Long perforated heavy-duty conveyor enclosed inside a sealed casing of approxim ately square cross section moves the waste though a tunnel; the	Consist of vessels (reactors) of different shapes and sizes; most approximat e the characterist ics of plug-flow (tubular) reactors or of continuousl y stirred tank reactors which are

						system approximates a plug flow reactor	common in process industry
Preprocessing	Material is mixed using standard agricultural equipment	Washing, precomposting, macerating or mixing. Precomposting is particularly beneficial.	Material is hand-sorted to prevent non compostables from getting into the composting bin.	Material is shredded and screened.	The drum itself is a precomposting unit; it homogenizes the waste and sets its decomposition process going	Material is shredded	Material is sorted to remove uncompostables
Turning/ aeration	No turning is done; to speed up the composting process, agrid of aeration or exhaust piping is used, over which substrate piles are formed.	No need for mechanical or forced aeration.	The composting mass is either left to natural aeration or turning is done at periodic intervals with simple garden equipment.	Frequency of turning is high during the early stages; progressively lesser with time Turning is accomplished using machines according to the scale of	As in the windrows	Air is blown through the conveyor or pan, and is exhausted from the casing top	A variety of mechanical and forced aeration systems are used

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				operation.			
Composting period	3–4 weeks	6-7 weeks	6–8 weeks	3–4 weeks	3–4 weeks	2–3 weeks	2–3 weeks
Curing period	4 weeks or longer	6-7 weeks	3–4 weeks	3–4 weeks without turning	3–4 weeks	3–4 weeks	3–4 weeks
Operation site	Contained pile systems can be used anywhere	Large area is required.	Ideal for household composting	Carried out in the outskirts of towns and cities to avoid disturbance to public. Operated as an addition to existing landfill operations.	As in the windrows	Suitable only where adequate land area is available	Can be installed everywhere at widely varying scales of operation

4.4 Proposing conceptual flowchart of smart waste management

The study on technological innovations in the smart e-waste management framework mainly relies on the conceptual flowchart presented in Figure-6. This updated framework addresses and overcomes the limitations identified in Figure-5, proposed by Roy et al. (2022). While Figure-4 laid the foundation for a sustainable e-waste management model, it lacked adequate integration of modern technological solutions, user engagement mechanisms, and policy compliance features necessary for effective implementation in Bangladesh.

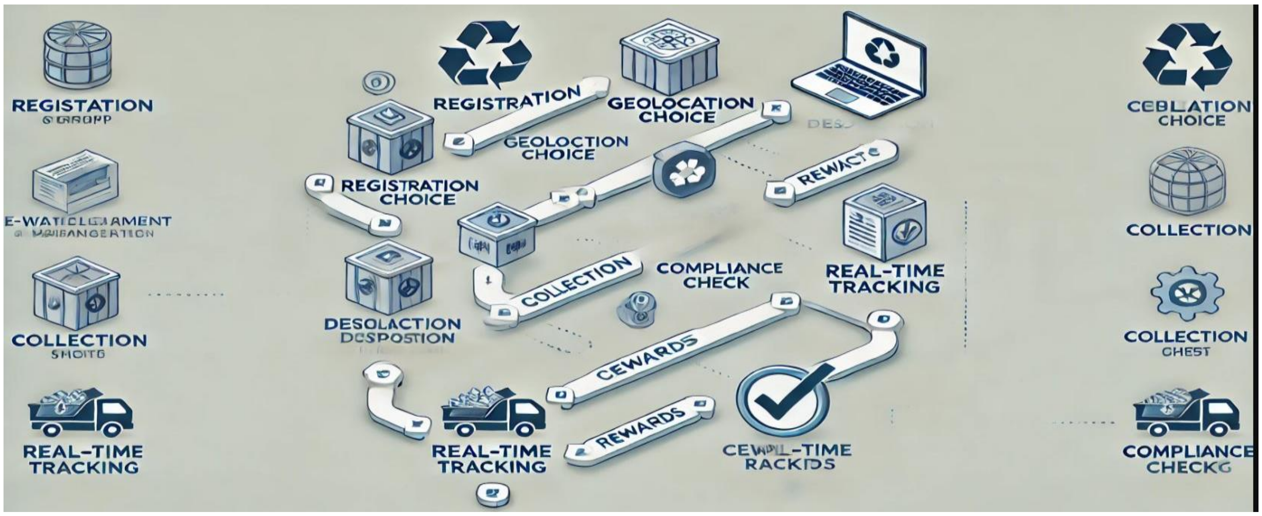

Figure -6. The conceptual flowchart of an E-waste management system. (Author Generated)

A key enhancement of the proposed flowchart is the integration of Internet of Things (IoT) and Artificial Intelligence (AI). These technologies enable real-time tracking of e-waste, optimize sorting and collection processes, and facilitate efficient resource recovery. Such features directly address the inefficiencies of informal recycling practices and align with the global shift towards sustainable development models (Das et al., 2022). By leveraging IoT and AI, the system can ensure that valuable resources, such as metals in printed circuit boards, are efficiently recovered, contributing significantly to economic opportunities.

The user-centric design of the flowchart is another major improvement. Users can register their e-waste through a streamlined process using email, phone, or social media platforms. Once registered, the system utilizes geolocation services to connect users with nearby authorized recycling centers or arranges for waste pickup. This accessibility ensures that the e-waste disposal process is straightforward and encourages widespread participation. Additionally, an incentive mechanism rewards users for environmentally responsible behaviors, fostering sustained engagement. This aspect of the framework aligns with the circular economy principle of encouraging reuse, repair, and recycling (Roy et al., 2022). To ensure legal and environmental compliance, the proposed flowchart incorporates a compliance checker. This feature verifies that all e-waste processing activities conform to national regulations, such as the 2021 Hazardous Waste (E-Waste) Management Act. By addressing enforcement and accountability gaps identified in the earlier framework, this component strengthens the regulatory backbone of the system (Kumar &Samadder, 2017).

The flowchart also emphasizes transparency and trust-building. Through real-time tracking capabilities, users can monitor the entire lifecycle of their e-waste—from collection to recycling. This transparency fosters trust and raises awareness about the environmental benefits of responsible e-waste disposal. Simultaneously, AI-driven waste categorization systems enhance efficiency by automatically sorting e-waste into specific types, such as smartphones, laptops, and household electronics. This optimization not only improves recycling operations but also maximizes resource recovery rates.

Moreover, the proposed framework underscores the importance of aligning policy and community efforts. Collaborative partnerships between the government, private stakeholders, and local communities are essential for scaling and maintaining the system. The framework also supports the inclusion of informal workers into the formal recycling sector, providing them with safer working conditions and sustainable livelihoods.

The proposed flowchart begins with user registration and geolocation-enabled connections to recycling centers. It incorporates waste categorization, compliance verification, and resource recovery stages, ensuring a smooth and efficient process. To encourage public participation, users are rewarded for eco-friendly disposal behaviors through an incentive system. Additionally, the system collects and analyzes data to refine operations, inform policy-making, and drive public awareness campaigns.

In conclusion, the conceptual flowchart (Figure 5) represents a comprehensive, eco-friendly, and technologically advanced approach to e-waste management. By addressing the limitations of Figure 4, the revised framework provides a more effective solution that integrates modern technologies, fosters user engagement, and ensures policy compliance. This framework aligns with the study's objectives, transforming e-waste management in Bangladesh into a sustainable, eco-friendly, and economically beneficial system. It also contributes significantly to the broader goals of sustainability and economic growth.

5. Conclusion

This study examined the challenges and opportunities in Bangladesh's e-waste management system, revealing significant inefficiencies in current practices dominated by informal recycling. The findings validate the first hypothesis, demonstrating that effective e-waste management can substantially reduce environmental pollution and improve public health by minimizing exposure to hazardous materials.

The proposed smart waste management framework, incorporating IoT and AI technologies, supports the second hypothesis by identifying considerable economic potential through metal recovery from e-waste. The integration of formal recycling practices with advanced technologies could transform waste management into a profitable venture while ensuring environmental sustainability.

The implementation of this study's findings requires a multi-stakeholder approach, combining policy reforms, technological innovation, and community engagement. The proposed conceptual flowchart provides a comprehensive framework for transitioning from informal to formal recycling practices, emphasizing user engagement and regulatory compliance.

A significant research gap remains in understanding the socio-economic impacts of formalizing the informal recycling sector, particularly regarding the transition of current workers, including vulnerable populations, into formal employment. Future studies should focus on developing scalable models for integrating informal workers into formal recycling systems while ensuring their economic security and safety.

Additionally, research is needed to evaluate the long-term effectiveness of smart waste management technologies in resource-constrained settings and their impact on public participation in proper e-waste disposal. This would help refine implementation strategies and maximize the benefits of technological solutions in developing countries like Bangladesh.

5.1 Limitations of the Study

Despite its comprehensive approach, this study has several limitations that must be acknowledged. Firstly, the data on e-waste generation, particularly in the informal sector, is incomplete and largely reliant on secondary sources, such as government reports and prior studies. This reliance may introduce inaccuracies or inconsistencies, as informal recycling activities often operate without proper documentation. Additionally, while the study emphasizes the economic potential of e-waste recycling, the financial models used to estimate potential revenues are based on idealized scenarios, which may not fully account for the operational challenges and market fluctuations inherent in Bangladesh's context.

Another limitation lies in the geographical scope. The study primarily focuses on urban areas such as Dhaka, where e-waste generation and management challenges are more apparent. This leaves out rural and semi-urban regions where informal recycling practices and associated risks may also be prevalent. The lack of field data from these areas limits the generalizability of the findings. Furthermore, the proposed technological solutions, such as IoT and AI-based management systems, have not been tested in real-world conditions within Bangladesh, raising questions about their feasibility in a resource-constrained environment.

Lastly, this study does not fully explore the socio-cultural factors that influence public behaviors and attitudes toward e-waste disposal. Understanding these factors is essential for designing effective awareness campaigns and policy interventions. Future research addressing these limitations can provide a more holistic view of e-waste management challenges and opportunities.

5.2 Future Research Directions

Future research should focus on collecting detailed data on e-waste generation and informal recycling across urban and rural areas to provide a comprehensive understanding of the issue.

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Pilot projects testing the feasibility and scalability of smart technologies, such as IoT and AI, in Bangladesh's context are essential. Additionally, exploring socio-cultural factors influencing public behaviors, with attention to gender and vulnerable groups, can inform targeted awareness campaigns and policy interventions. Evaluating the impact of existing regulations and studying interdisciplinary approaches integrating environmental science, economics, and public health can further enhance sustainable e-waste management strategies tailored to Bangladesh's needs.

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