

Material Flow Analysis of Electronic Waste Management for Sustainable Urban Resource Management in Gazipur City Bangladesh

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Abstract

Electronic waste (e-waste) is one of the fastest-growing waste streams worldwide, posing significant environmental and public health challenges, particularly in developing countries where recycling is dominated by the informal sector. This study quantifies e-waste generation, material flows, and management practices in Gazipur City Corporation, Bangladesh, using Material Flow Analysis (MFA) integrated with household surveys ($n = 375$), stakeholder interviews, field observations, and secondary data. Approximately 6,245.21 tonnes of e-waste were generated in 2024, equivalent to $2.43 \text{ kg capita}^{-1} \text{ year}^{-1}$. Large household appliances accounted for the largest share of the waste stream, with refrigerators (42.05%), televisions (19.44%), and microwave ovens (9.26%) being the major contributors. Nearly 47% of e-waste was managed through informal collection and recycling networks or disposed of with municipal solid waste, increasing environmental and health risks. Key barriers included inadequate collection infrastructure, weak regulatory enforcement, limited public awareness, and the absence of effective Extended Producer Responsibility (EPR). The study recommends strengthening formal collection systems, integrating informal recyclers into regulated recycling networks, and implementing EPR within a circular economy framework to improve resource recovery. These findings provide quantitative evidence to support sustainable urban resource management and e-waste policy development in rapidly urbanizing low- and middle-income countries.

1. Introduction

Electronic waste (e-waste), which comprises discarded electrical and electronic equipment (EEE) and their components, is one of the fastest-growing waste streams globally. Rapid technological advancement, urbanization, rising household incomes, and increasingly shorter product life cycles have significantly accelerated the consumption and disposal of electronic products over the past two decades (Forti, Baldé et al. 2020, Baldé, D'angelo et al. 2022). According to the Global E-waste Monitor 2024, approximately 62 million tons of e-waste were generated globally in 2022, representing an 82% increase since 2010. However, only 22.3% of this waste entered documented formal collection and recycling systems, while the remaining fraction was landfilled, openly burned, illegally traded, or processed through informal recycling activities (Forti, Baldé et al. 2020). This growing gap between e-waste generation and environmentally sound recycling has become a major challenge for sustainable resource management worldwide.

Although e-waste poses significant environmental risks, it also represents an important urban resource. Discarded electrical and electronic equipment contains valuable secondary raw materials, including gold, silver, copper, aluminium, palladium, and rare earth elements, which can be recovered to reduce dependence on primary resource extraction and support circular economy initiatives (Awasthi, Li et al. 2019, Forti, Baldé et al. 2020). Conversely, electronic products also contain hazardous substances such as lead (Pb), cadmium (Cd), mercury (Hg), hexavalent chromium (Cr^{6+}), brominated flame retardants (BFRs), and polychlorinated biphenyls (PCBs). Improper collection, dismantling, recycling, and disposal can release these contaminants into soil, surface water, groundwater, and the atmosphere, causing

environmental degradation and posing significant risks to ecosystems and human health(Kiddee, Naidu et al. 2013, Perkins, Drisse et al. 2014).

The challenges associated with e-waste management are particularly severe in developing countries, where formal recycling systems remain inadequate and informal sectors dominate collection and material recovery(Widmer, Oswald-Krapf et al. 2005, Nnorom and Osibanjo 2008). Informal recycling commonly involves manual dismantling, open burning of insulated cables, acid leaching, and uncontrolled disposal of non-recyclable residues without adequate environmental protection or occupational safety measures(Grant, Goldizen et al. 2013, Kiddee, Naidu et al. 2013). These practices expose workers and nearby communities to hazardous pollutants linked to respiratory diseases, neurological disorders, endocrine disruption, reproductive toxicity, kidney dysfunction, and increased cancer risk(Pannu, Siciliano et al. 2014, Organization 2021). Consequently, environmentally sound e-waste management has become an essential component of sustainable development and contributes directly to the achievement of the United Nations Sustainable Development Goals (SDGs), particularly SDG 3 (Good Health and Well-being), SDG 11 (Sustainable Cities and Communities), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action)(Sayed 2015).

Bangladesh has experienced rapid industrialization, urban expansion, digital transformation, and increasing ownership of electrical and electronic equipment over the past decade. These changes have resulted in a continuous rise in e-waste generation from households, commercial establishments, educational institutions, healthcare facilities, and manufacturing industries(Masud, Akram et al. 2019, Roy, Rahman et al. 2022). Despite this increasing waste stream, formal collection, recycling infrastructure, and regulatory enforcement remain limited, while e-waste management continues to rely heavily on informal collectors, scrap dealers, repair workshops, and small-scale recyclers operating with minimal environmental safeguards(Rashid, Alam et al. 2022, Sarker, Sarker et al. 2025). Consequently, substantial quantities of valuable materials are lost, hazardous substances are released into the environment, and workers are exposed to significant occupational health risks.

Gazipur City Corporation (GCC) is one of the largest industrial and fastest-growing urban centres in Bangladesh. The city hosts extensive ready-made garment industries, engineering and electronics manufacturing facilities, pharmaceutical industries, educational institutions, commercial establishments, and rapidly expanding residential areas(BBS 2011, Gupta and Gulati 2026). These socio-economic characteristics have substantially increased the consumption of electrical and electronic equipment and consequently the generation of e-waste. Despite the growing body of research on e-waste management in Bangladesh, important knowledge gaps remain regarding city-level material flow assessment. Most existing studies have focused on national e-waste generation estimates, consumer disposal behaviour, informal recycling practices, or policy-related issues, whereas comprehensive investigations that quantify the generation, collection, recycling, recovery, and disposal of e-waste using a Material Flow Analysis (MFA) framework are still limited(Islam and Huda 2019, Masud, Akram et al. 2019, Ananno, Masud et al. 2021). Furthermore, little empirical evidence is available on the interaction between formal and informal e-waste management systems in rapidly industrializing cities such as Gazipur, where

increasing electronic consumption has intensified resource recovery challenges and environmental risks. The absence of detailed city-scale material flow information constrains evidence-based municipal planning, effective implementation of Extended Producer Responsibility (EPR), and the development of circular economy strategies for sustainable urban resource management.

Material Flow Analysis (MFA) is a well-established analytical framework for quantifying the flow and accumulation of materials within a defined system. It enables the identification of material inputs, stocks, recycling pathways, resource recovery potential, and losses throughout the product life cycle, thereby supporting evidence-based decision-making for waste management and circular economy implementation (Brunner and Rechberger 2016, Islam and Huda 2019). When combined with household surveys, stakeholder interviews, field observations, and institutional assessments, MFA provides a comprehensive understanding of e-waste generation and management systems while identifying opportunities to improve collection efficiency, recycling performance, and resource recovery (González-García, Hospido et al. 2011).

Therefore, this study applies an integrated Material Flow Analysis framework to quantify e-waste generation, characterize material flows, evaluate existing collection and recycling pathways, and identify institutional and operational challenges in Gazipur City Corporation, Bangladesh. By integrating quantitative data from household surveys with qualitative information obtained through stakeholder interviews and field observations, this study provides one of the first comprehensive city-level Material Flow Analysis (MFA)-based assessments of e-waste generation and management in Bangladesh. The findings contribute to the scientific understanding of material cycles in rapidly urbanizing cities and provide evidence to support municipal planning, strengthen formal recycling systems, improve resource recovery, facilitate the implementation of Extended Producer Responsibility (EPR), and promote circular economy strategies for sustainable urban resource management.

1.1 Research Objectives

The objectives of this study are to:

1. Quantify e-waste generation in Gazipur City Corporation using Material Flow Analysis (MFA).
2. Characterize the major sources, categories, and material flows of generated e-waste.
3. Evaluate formal and informal collection, recycling, recovery, and disposal pathways.
4. Identify institutional, regulatory, socio-economic, and operational barriers affecting sustainable e-waste management.
5. Propose evidence-based strategies to improve resource recovery, strengthen circular economy implementation, and support sustainable urban e-waste management.

2. Materials and Methods

2.1 Study Area

Gazipur City Corporation (GCC), Bangladesh, was selected as the study area because of its rapid industrialization, urban expansion, and increasing consumption of electrical and electronic equipment (EEE). The selection of Gazipur City Corporation aligns with the objective of this study because the city represents one of Bangladesh's fastest-growing industrial and urban centres, where increasing ownership of electrical and electronic equipment has accelerated e-waste generation and intensified resource management challenges. Located immediately north of Dhaka, Gazipur has developed into one of the country's major industrial and manufacturing centres, with a strong concentration of ready-made garment, textile, pharmaceutical, engineering, and electronics industries (Statistics 2011, Corporation 2024). The city's rapid socio-economic development, accompanied by population growth and technological advancement, has led to a substantial increase in the consumption of electronic products and the generation of electronic waste (e-waste).

Gazipur City Corporation, located immediately north of Dhaka, covers an area of approximately 329.53 km² and is administratively divided into 57 wards across eight operational zones (Table 1). Geographically, the city lies between 23°52'45"–24°06'12" N latitude and 90°15'02"–90°29'50" E longitude (Fig. 1). According to the Bangladesh Bureau of Statistics (BBS), Gazipur has a population exceeding 2.5 million, making it one of the largest and fastest-growing metropolitan areas in Bangladesh (BBS 2011). As one of the country's major industrial and manufacturing hubs, characterized by rapid urbanization, a high population density, expanding commercial activities, and increasing household incomes, Gazipur has experienced substantial growth in the consumption of electrical and electronic equipment (EEE). Consequently, the generation of electronic waste (e-waste) has increased considerably, posing significant environmental and public health challenges (Borthakur and Govind 2017, Islam and Huda 2018, Forti, Baldé et al. 2020).

Despite its economic importance, Gazipur's formal e-waste management system remains underdeveloped. The collection, repair, dismantling, and recycling of end-of-life electrical and electronic equipment are predominantly undertaken by the informal sector, including itinerant waste collectors, Bhangari (scrap) shops, repair workshops, and small-scale dismantling enterprises. Limited formal collection facilities, inadequate recycling infrastructure, and weak regulatory implementation continue to constrain environmentally sound e-waste management in Bangladesh (Roy, Alam et al. 2022, Fatema, Hassan et al. 2025). These characteristics make Gazipur City Corporation an appropriate case study for evaluating urban e-waste generation, material flows, recycling pathways, and sustainable resource management.

Table 1
Administrative Zones of Gazipur City Corporation

Zone	Area (km ²)
Zone 1 (Tongi)	32.36
Zone 2 (Pubail)	49.00
Zone 3 (Gaccha)	28.68
Zone 4 (Gazipur Sadar)	48.50
Zone 5 (Kashimpur/Koyaltia)	69.88
Zone 6 (Basan)	28.66
Zone 7 (Konabari)	22.15
Zone 8 (Kashimpur)	50.30
Total	329.53

2.2 Research Design

A convergent mixed-methods research design was adopted to evaluate e-waste generation and management in Gazipur City Corporation, Bangladesh. Quantitative and qualitative data were collected concurrently between January and December 2024 and integrated during the interpretation stage using methodological triangulation to improve the validity and comprehensiveness of the findings (Creswell and Clark 2017).

The quantitative component employed Material Flow Analysis (MFA) to estimate annual e-waste generation and characterize material flows within the study area. MFA is a widely used analytical framework for quantifying the movement and accumulation of materials within defined systems and has been extensively applied in waste management and circular economy studies (Brunner and Rechberger 2016). Primary quantitative data were collected using structured questionnaires administered to 375 respondents, including households, informal recyclers, scrap (Bhangari) shop owners, repair shops, institutional representatives, and government officials.

The qualitative component consisted of key informant interviews (KIIs) and direct field observations to examine e-waste collection practices, recycling activities, institutional arrangements, regulatory implementation, and operational challenges. These methods provided contextual information that complemented the quantitative results and facilitated a better understanding of existing e-waste management practices. The quantitative and qualitative findings were subsequently integrated through methodological triangulation to provide a comprehensive assessment of e-waste generation, material flows, recycling pathways, institutional capacity, and sustainability challenges in Gazipur City.

Corporation(Creswell and Clark 2017). The overall methodological framework is presented in Fig. 2, while the framework used to assess e-waste management practices is shown in Fig. 3.

2.3 Data Collection

Data were collected from both primary and secondary sources between January and December 2024 to assess e-waste generation, material flows, and management practices in Gazipur City Corporation (GCC), Bangladesh.

Primary data were obtained through structured questionnaire surveys, key informant interviews (KIIs), and direct field observations. The household questionnaire gathered information on the ownership of electrical and electronic equipment (EEE), product lifespan, replacement frequency, storage practices, disposal behaviour, and public awareness of e-waste management. Interviews with informal-sector stakeholders focused on collection systems, dismantling methods, material recovery, occupational health and safety, and the economic aspects of recycling. Institutional interviews explored existing policies, collection mechanisms, regulatory implementation, operational constraints, and future management strategies.

Field observations were conducted at households, Bhangari (scrap) shops, repair workshops, informal dismantling sites, temporary storage facilities, and municipal disposal locations. These observations were used to verify survey responses and document actual e-waste handling, dismantling, and recycling practices.

Secondary data were obtained from Gazipur City Corporation (GCC), the Bangladesh Bureau of Statistics (BBS), the Department of Environment (DoE), government reports, and relevant peer-reviewed literature to complement and validate the primary survey findings(BBS 2011, Roy, Rahman et al. 2022, Corporation 2024).

2.3.1 Sampling Strategy

A combination of stratified and purposive sampling techniques was employed to ensure adequate representation of the principal stakeholder groups involved in e-waste generation and management(Creswell and Clark 2017). Household respondents were selected using stratified sampling across the eight operational zones of Gazipur City Corporation to capture geographical and socio-economic variation. Informal-sector participants—including waste collectors, Bhangari (scrap) shop owners, repair technicians, dismantlers, and e-waste traders—were selected purposively based on their active involvement in e-waste collection and recycling activities. Institutional respondents were also selected purposively from Gazipur City Corporation, the Department of Environment (DoE), educational institutions, recycling enterprises, and non-governmental organizations because of their roles in e-waste governance and management.

A total of 375 respondents participated in the study, comprising 197 household representatives, 133 informal-sector stakeholders, and 45 institutional representatives. This sampling approach ensured adequate representation of the principal actors involved in e-waste generation, collection, recycling, and regulatory management within the study area.

2.4 Material Flow Analysis (MFA)

Material Flow Analysis (MFA) was employed to quantify electronic waste (e-waste) generation and to trace the movement of discarded electrical and electronic equipment (EEE) within Gazipur City Corporation. MFA is a standardized analytical method used to quantify material inputs, stocks, flows, and outputs within a defined system. It has been widely applied to assess waste management systems, resource recovery, and circular economy performance by identifying material losses and recycling pathways (Oguchi, Murakami et al. 2011, Brunner and Rechberger 2016, Islam and Huda 2019).

The system boundary of this study encompassed households, commercial establishments, educational institutions, government offices, informal collection networks, repair workshops, recycling facilities, temporary storage locations, and final disposal sites within Gazipur City Corporation. Based on field data collected during 2024, the movement of e-waste was traced from the point of generation through collection, reuse, repair, informal recycling, formal recycling (where applicable), temporary storage, and final disposal. This system-based approach enabled the identification of major material flow pathways and the estimation of resource recovery and material leakage into the municipal solid waste stream (Brunner and Rechberger 2016, Islam and Huda 2019).

Annual e-waste generation was estimated using:

$$EW = \sum_{i=1}^n \left(\frac{N_i \times W_i}{L_i} \right)$$

where:

- EW = annual e-waste generation (kg year⁻¹)
- N_i = number of products owned
- W_i = average product weight (kg)
- L_i = average service life (years)

Average product weights and service-life values were compiled from published literature, the Global E-waste Monitor, manufacturer specifications, and previous Material Flow Analysis (MFA) studies (Oguchi, Murakami et al. 2011, Baldé, Kuehr et al. 2024). Ownership and replacement data were obtained through the household survey. Estimated e-waste quantities were subsequently aggregated across product categories to determine the annual e-waste generation in Gazipur City Corporation.

The material flow model classified discarded EEE into six principal pathways: (i) reuse, (ii) repair, (iii) informal recycling, (iv) formal recycling, (v) temporary storage, and (vi) final disposal. The resulting MFA

was used to estimate material recovery, identify losses to the municipal waste stream, and evaluate opportunities for improving resource efficiency and circular e-waste management.

2.5 Data Analysis

Survey data were entered, cleaned, and analyzed using Microsoft Excel 2021 and IBM SPSS Statistics (Version 26). Descriptive statistical analyses, including frequencies, percentages, means, and summary tables, were used to characterize household ownership of electrical and electronic equipment, disposal behavior, and stakeholder responses. Material Flow Analysis (MFA) was performed using Microsoft Excel to estimate annual e-waste generation and quantify material flows through reuse, repair, recycling, storage, and disposal pathways (Brunner and Rechberger 2016). Qualitative data obtained from key informant interviews and field observations were analyzed using thematic content analysis (Braun and Clarke 2006) and integrated with quantitative findings through methodological triangulation to enhance the validity and interpretation of the results (Creswell and Clark 2017).

2.6 Ethical Considerations

Participation in the household questionnaire survey and key informant interviews was entirely voluntary. Before data collection, all participants were provided with clear information about the objectives of the study, the nature and procedures of their participation, the intended use of the collected information, and their right to decline participation or withdraw from the study at any stage without consequence. Freely given and informed consent was obtained verbally from all participants before participation in the questionnaire survey or interviews. All participants were older than 16 years of age. Participants were informed that their responses would be anonymized and treated confidentially and that the collected data would be used exclusively for academic research purposes and reported only in aggregate form to prevent the identification of individual participants. The study was conducted in accordance with the ethical principles outlined in the Declaration of Helsinki (De Helsinki 2013).

2.7 Assumptions and Limitations of the Material Flow Analysis

The Material Flow Analysis (MFA) was conducted based on several assumptions. Average product weights and expected service lives for different categories of electrical and electronic equipment were obtained from published literature and manufacturer specifications (Oguchi, Murakami et al. 2011, Brunner and Rechberger 2016), whereas information on product ownership, replacement frequency, and disposal practices was derived from the household survey. The analysis assumed that respondents accurately reported product ownership and replacement behavior and that the selected sample was reasonably representative of Gazipur City Corporation. Material flows were estimated using annual average values and therefore do not account for seasonal or short-term variations in purchasing or disposal behavior. In addition, some informal recycling activities could not be fully quantified because of limited record-keeping within the informal sector. Despite these limitations, the integration of household surveys, stakeholder interviews, field observations, and secondary data provides a robust basis for

estimating e-waste generation and evaluating material flows within the study area(Brunner and Rechberger 2016).

3. Results and Discussion

3.1 Ownership of Electrical and Electronic Equipment

Household survey results indicated widespread ownership of electrical and electronic equipment (EEE) in Gazipur City Corporation, reflecting rapid urbanization, rising living standards, and increasing dependence on electronic technologies (Table 4.1). Electric fans represented the largest share of household appliances (36.23%), followed by mobile phones (11.55%), televisions (11.43%), refrigerators (9.18%), computers/laptops (6.75%), and air conditioners (5.42%). Other small household appliances accounted for the remaining 19.44%.

The predominance of cooling appliances reflects local climatic conditions, whereas the increasing ownership of communication and information technologies indicates continuing digitalization. These consumption patterns suggest that the volume of end-of-life electronic products will continue to increase over the coming years. Similar trends have been reported globally, where technological advancement and increasing household income have accelerated both electronic product consumption and e-waste generation(Forti, Baldé et al. 2020). The high ownership of large household appliances also indicates substantial future potential for recovering secondary materials, including ferrous metals, aluminum, copper, and plastics.

3.2 E-Waste Generation

Material Flow Analysis (MFA) estimated that Gazipur City Corporation generated approximately 6,245.21 tons of e-waste in 2024. The household sector accounted for approximately 97.3% of total generation, while commercial and institutional sources contributed the remaining 2.7%. he estimated per-capita e-waste generation rate was 2.43 kg person⁻¹ year⁻¹ (Table 2), which is considerably lower than the global average of 7.8 kg person⁻¹ year⁻¹ reported in the Global E-waste Monitor 2024 but comparable to recent national estimates for Bangladesh(Baldé, Kuehr et al. 2024). A comparison of the estimated per-capita e-waste generation in Gazipur City Corporation with national, regional, and global averages is presented in Table 3.

Table 2
Comparison of Per Capita E-waste Generation

Region/City	Year	Per capita e-waste generation (kg person ⁻¹ year ⁻¹)	Reference
Gazipur City Corporation	2024	2.43	Present study
Bangladesh (national estimate)	2022	2.5–3.0	(Forti, Baldé et al. 2020)
Asia (average)	2022	6.4	(Forti, Baldé et al. 2020)
Global average	2022	7.8	(Forti, Baldé et al. 2020)
European Union	2022	17.6	(Forti, Baldé et al. 2020)

This difference is likely attributable to lower household purchasing power, longer product use cycles, and a relatively lower penetration of high-value electrical and electronic equipment compared with high-income countries (Baldé, Kuehr et al. 2024). Large household appliances, particularly refrigerators and televisions, contributed most of the total e-waste mass because of their relatively high individual weights. Conversely, mobile phones and other small electronic devices were replaced more frequently but contributed less to the overall waste mass. This pattern agrees with previous international studies demonstrating that household appliances dominate e-waste by weight, whereas information and communication technology devices dominate the number of discarded products (Lau, Chung et al. 2013, Parajuly, Habib et al. 2017, Baldé, Kuehr et al. 2024). These estimates provide an important baseline for municipal planning and highlight the need to expand formal collection systems, recycling infrastructure, and Extended Producer Responsibility (EPR) programs.

3.3 Existing E-Waste Management System

The survey and field observations revealed that e-waste management in Gazipur City Corporation is largely controlled by the informal sector. Informal waste collectors (*Bhangari*) collected 52.63% of discarded electronic products, while 44.93% entered scrap trading and dismantling activities for material recovery. Direct disposal without recovery represented only a small proportion of total e-waste generation. The overall movement of e-waste from generation through collection, dismantling, recycling, material recovery, and final disposal is illustrated in the Material Flow Analysis (MFA) Sankey diagram (Fig. 4).

The diagram highlights the dominant role of informal collection and recycling pathways, as well as the leakage of a substantial proportion of e-waste into the municipal solid waste stream.

Despite the contribution of informal collectors to resource recovery, approximately 47% of household e-waste was mixed with municipal solid waste because source-separated collection systems are largely absent. This practice reduces recycling efficiency and increases material losses.

Field observations further indicated that recycling activities relied mainly on manual dismantling, open burning of insulated cables, and uncontrolled disposal of residual materials. Limited use of personal protective equipment exposed workers to hazardous substances such as lead, mercury, cadmium, and brominated flame retardants. Comparable practices have been documented in many developing countries, where informal recycling contributes significantly to resource recovery but operates under inadequate environmental and occupational safety standards. These findings emphasize the need to integrate informal recyclers into regulated recycling systems while improving collection efficiency and environmental protection.

3.4 Future E-Waste Generation Scenario

Based on the 2024 baseline, a scenario analysis assuming an annual growth rate of 20% projected that e-waste generation could increase to approximately 143,097 tonnes year⁻¹ by 2041 (Table 3). Although this represents a hypothetical scenario rather than a prediction, it illustrates the substantial pressure that continued urbanization, industrial development, and increasing electronic product consumption may place on existing waste management systems.

Without improvements in collection efficiency, recycling capacity, and policy implementation, increasing e-waste generation is likely to reduce resource recovery while increasing environmental pollution and human health risks. These findings demonstrate the importance of long-term planning and investment in environmentally sound recycling infrastructure.

Table 3
Estimated future E-Waste generation in Gazipur City (2024–2041)

Year	Total E waste (tons/yr)
2024	6,245.21
2029	15,540.08
2034	38,543.30
2039	102,214.10
2041	143,097.12

3.5 Discussion

The present study provides one of the first city-scale assessments of electronic waste (e-waste) generation and material flows in Gazipur City Corporation using an integrated Material Flow Analysis (MFA) framework supported by primary field data. The estimated generation of 6,245.21 tones year⁻¹ demonstrates that e-waste is becoming an increasingly important component of the municipal waste stream as industrialization, urbanization, and household ownership of electrical and electronic

equipment continue to increase. The estimated per-capita e-waste generation rate ($2.43 \text{ kg person}^{-1} \text{ year}^{-1}$) is substantially lower than the global average ($7.8 \text{ kg person}^{-1} \text{ year}^{-1}$) reported in the Global E-waste Monitor 2024 but is comparable to recent national estimates for Bangladesh (Baldé, Kuehr et al. 2024). This difference is likely associated with comparatively lower household purchasing power, longer product service lives resulting from repair and reuse practices, and lower ownership of high-value electronic equipment than in high-income countries (Kiddee, Naidu et al. 2013, Kumar, Holuszko et al. 2017, Baldé, Kuehr et al. 2024). Similar differences between developing and developed countries have also been reported in previous Material Flow Analysis studies (Lau, Chung et al. 2013, Parajuly, Habib et al. 2017).

The predominance of large household appliances in the total e-waste mass indicates considerable opportunities for recovering valuable secondary materials, including ferrous and non-ferrous metals, plastics, and other recyclable components. This finding is consistent with previous Material Flow Analysis studies, which reported that refrigerators, televisions, and other large household appliances account for the largest proportion of e-waste by mass because of their relatively high individual weights, whereas smaller ICT devices contribute a larger number of discarded products owing to their shorter replacement cycles (Lau, Chung et al. 2013, Parajuly, Habib et al. 2017, Baldé, Kuehr et al. 2024). Improving the recovery of these materials would contribute to resource efficiency, reduce dependence on virgin raw materials, and support circular economy objectives (Huang, Bi et al. 2007, Kirchherr, Reike et al. 2017).

The findings further reveal that e-waste management in Gazipur City Corporation remains heavily dependent on the informal sector. Informal collectors, repair shops, and scrap dealers play an essential role in collecting discarded electronic products and recovering reusable materials. However, reliance on informal recycling practices reflects the absence of well-developed formal collection and recycling systems. Manual dismantling, open burning of insulated cables, and uncontrolled handling of hazardous components substantially increase the release of toxic substances into the environment while exposing workers to serious occupational health risks. Similar conditions have been documented in India, China, Ghana, Nigeria, and several other developing countries, where informal recycling contributes to resource recovery but remains environmentally unsustainable because of inadequate regulation and limited technological capacity (Kiddee, Naidu et al. 2013, Perkins, Drisse et al. 2014, Masud, Akram et al. 2019, Hou, Lan et al. 2023).

Several institutional barriers were also identified, including the absence of source segregation, inadequate formal collection and recycling infrastructure, weak enforcement of environmental regulations, and limited public awareness. These constraints reduce recycling efficiency, increase material leakage into the municipal solid waste stream, and limit the recovery of valuable resources. Similar institutional challenges have been identified as major obstacles to sustainable e-waste management in many low- and middle-income countries (Nnorom and Osibanjo 2008, Masud, Akram et al. 2019).

The future scenario analysis further emphasizes the need for proactive municipal planning and policy intervention. Strengthening formal collection systems, implementing Extended Producer Responsibility (EPR), expanding environmentally sound recycling infrastructure, and integrating informal recyclers into regulated recycling systems through training and certification would improve resource recovery while reducing environmental and public health risks. These measures are consistent with international recommendations for achieving sustainable material cycles, improving resource efficiency, and promoting a circular economy for waste electrical and electronic equipment (Awasthi, Li et al. 2019, Islam and Huda 2019, Forti, Baldé et al. 2020).

From the perspective of sustainable urban resource management, the Material Flow Analysis demonstrates that e-waste should be regarded not merely as a waste management challenge but also as an important source of secondary raw materials (Hageluken 2006, Kennedy, Cuddihy et al. 2007). Recovering metals, plastics, glass, and reusable electronic components can reduce dependence on virgin resources, improve material efficiency, decrease environmental pollution, and support the transition towards a circular economy (Helmut 2003, Tukker 2015, Kirchherr, Reike et al. 2017, Stahel 2019). Therefore, integrating Material Flow Analysis into municipal planning and decision-making can enhance resource recovery, strengthen evidence-based e-waste policies, and improve the long-term sustainability of rapidly urbanizing cities such as Gazipur (Helmut 2003, Fischer-Kowalski and Haberl 2007, Kennedy, Cuddihy et al. 2007).

3.6 Resource Recovery Potential

Electronic waste generated in Gazipur City Corporation represents not only an environmental challenge but also a significant source of secondary raw materials. The estimated 6,245.21 tons of e-waste generated annually contains recoverable materials such as ferrous metals, aluminium, copper, plastics, glass, and reusable electronic components. Large household appliances, particularly refrigerators and televisions, account for a substantial proportion of the total waste mass and therefore offer considerable opportunities for material recovery and resource conservation (Awasthi, Li et al. 2019, Forti, Baldé et al. 2020).

Field observations indicated that informal recyclers currently recover recyclable materials primarily through manual dismantling and component separation. Copper wiring, aluminium frames, steel casings, electric motors, compressors, plastics, and reusable electronic components constitute the principal materials recovered for resale. However, valuable precious metals contained in printed circuit boards, including gold, silver, palladium, and rare earth elements, are seldom recovered locally because of limited technological capacity and inadequate recycling infrastructure (Kiddee, Naidu et al. 2013, Baldé, Kuehr et al. 2024).

The absence of environmentally sound recycling facilities reduces recovery efficiency and results in the loss of valuable secondary resources. Furthermore, informal recycling practices, including open burning of insulated cables and uncontrolled dismantling, increase emissions of hazardous substances while reducing the economic value of recovered materials (Perkins, Drisse et al. 2014, Islam and Huda 2019).

Establishing formal recycling facilities equipped with modern dismantling and material separation technologies would substantially improve recovery efficiency, reduce dependence on virgin raw materials, and strengthen circular material flows (Brunner and Rechberger 2016, Forti, Baldé et al. 2020).

Strengthening source-segregated collection systems, implementing Extended Producer Responsibility (EPR), and integrating informal recyclers into regulated recycling networks would further enhance resource recovery while minimizing environmental pollution and occupational health risks. These measures are consistent with international recommendations for promoting sustainable resource management and advancing a circular economy for waste electrical and electronic equipment (Awasthi, Li et al. 2019, Forti, Baldé et al. 2020, Pauliuk, Fishman et al. 2021).

4. Conclusion

This study applied Material Flow Analysis (MFA) integrated with household surveys, stakeholder interviews, and field observations to quantify electronic waste (e-waste) generation and evaluate existing management practices in Gazipur City Corporation, Bangladesh. The findings provide a comprehensive city-scale empirical assessment of e-waste material flows in Bangladesh and establish a baseline for sustainable urban resource management.

The analysis estimated that Gazipur City Corporation generated approximately 6,245.21 tonnes of e-waste in 2024, corresponding to a per-capita generation rate of 2.43 kg person⁻¹ year⁻¹. Households were identified as the principal source of e-waste, with large household appliances contributing the greatest share of the total waste mass. The material flow assessment demonstrated that e-waste management is dominated by informal collection and recycling networks. Although these networks recover economically valuable materials such as ferrous metals, aluminium, copper, plastics, and reusable components, recycling practices are generally conducted using environmentally unsound techniques with limited occupational health and safety measures. Furthermore, the absence of source-segregated collection and dedicated e-waste recycling facilities allows a considerable proportion of discarded electronic products to enter the municipal solid waste stream, reducing resource recovery efficiency and increasing environmental risks.

The scenario analysis indicates that continued urbanization, industrial expansion, and increasing ownership of electrical and electronic equipment are likely to accelerate future e-waste generation, thereby increasing pressure on municipal collection systems, recycling infrastructure, and environmental management unless appropriate policy interventions are implemented. Without timely improvements in collection systems, recycling infrastructure, and institutional capacity, increasing e-waste volumes may intensify environmental pollution, material losses, and public health risks while limiting opportunities for secondary resource recovery.

The findings highlight the importance of strengthening formal collection systems, establishing environmentally sound recycling facilities, implementing Extended Producer Responsibility (EPR), and integrating informal recyclers into regulated management systems through technical training and

improved occupational safety. Expanding source-segregated collection and public awareness initiatives would further improve recycling efficiency and promote the recovery of valuable secondary materials, thereby supporting the transition toward a circular economy. Collectively, these measures would strengthen sustainable urban resource management by improving resource recovery, enhancing resource efficiency, reducing environmental pollution, and supporting the transition toward a circular economy.

Overall, this research provides scientific evidence to support evidence-based municipal planning and e-waste governance in rapidly urbanizing cities of Bangladesh. By integrating Material Flow Analysis (MFA) with field-based evidence, the study contributes to the advancement of circular economy strategies and sustainable urban resource management. Future research should focus on life cycle assessment, quantitative evaluation of resource recovery efficiency, economic feasibility of formal recycling systems, and assessment of policy effectiveness to further improve environmentally sound e-waste management.

Declarations

Funding

No funding was received for this study.

Data Availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Clinical trial number

Clinical trial number: not applicable.

Ethical Approval and accordance

This study involved data collection from human participants through household surveys and stakeholder interviews. Participation was entirely voluntary. Before data collection, all participants were informed about the objectives and nature of the study, the type of information requested, the intended use of the collected information, and their right to decline participation or withdraw from the study at any stage without consequence. Freely given and informed consent was obtained verbally from all participants before their participation in the household surveys and stakeholder interviews. All participants were older than 16 years of age. No personally identifiable information was collected or reported in this study. All responses were anonymized and treated confidentially, and the collected information was used exclusively for academic research purposes and reported only in aggregate form.

Ethical approval and accordance: Prior to the commencement of data collection, the study received ethical approval from the Committee for Advanced Studies and Research (CASR), Dhaka University of

Engineering & Technology (DUET), Gazipur, Bangladesh. The study was conducted in accordance with the research ethics guidelines of the Institute of Water and Environment, Dhaka University of Engineering & Technology (DUET), Gazipur, Bangladesh, and all research procedures were conducted in accordance with the ethical standards and guidelines approved by the institution. The study was conducted in accordance with the ethical principles outlined in the Declaration of Helsinki (De Helsinki 2013).

Consent to Publish

Consent to publish is not applicable because the manuscript does not contain identifiable personal information, photographs, or other material that could identify individual participants.

Data Availability and Sources of Secondary Data

The datasets used and/or analyzed during the current study are available from the following publicly accessible sources:

1. Gazipur City Corporation (GCC)(Corporation 2023)

<https://gcc.gov.bd/>

2. Department of Environment (DoE), Bangladesh(Department of Environment 2026)

<https://doe.gov.bd/pages/static-pages/6922dfe3933eb65569e24824>

3. Bangladesh Bureau of Statistics (BBS)(Bangladesh Bureau of Statistics 2026)

<https://bbs.gov.bd/pages/static-pages/6922dcc8933eb65569e12081>

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Figures

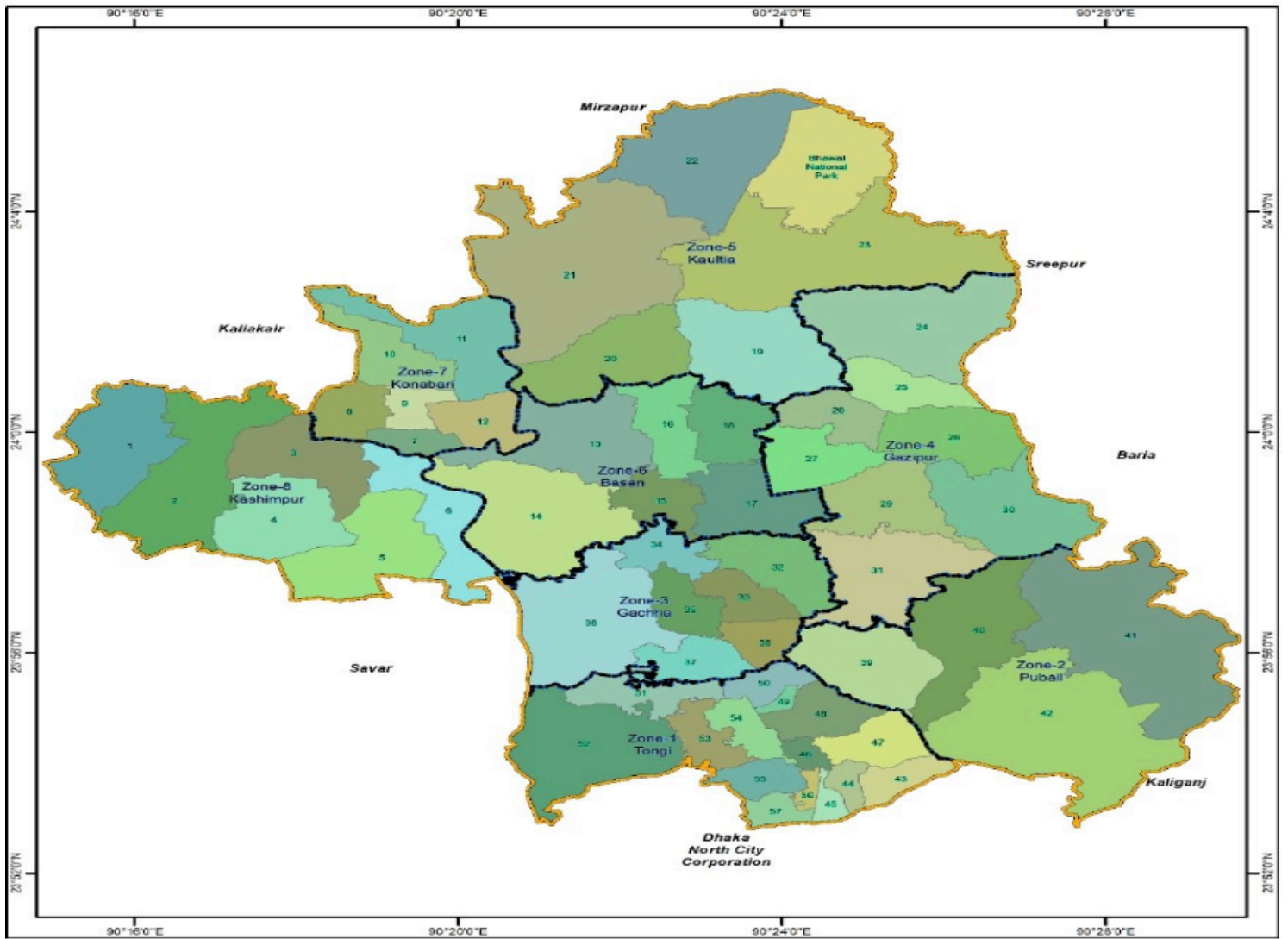


Figure 1

Map of Eight Different Zones in GCC (Source: CRTS, Department of Civil Engineering, DUET, Gazipur)

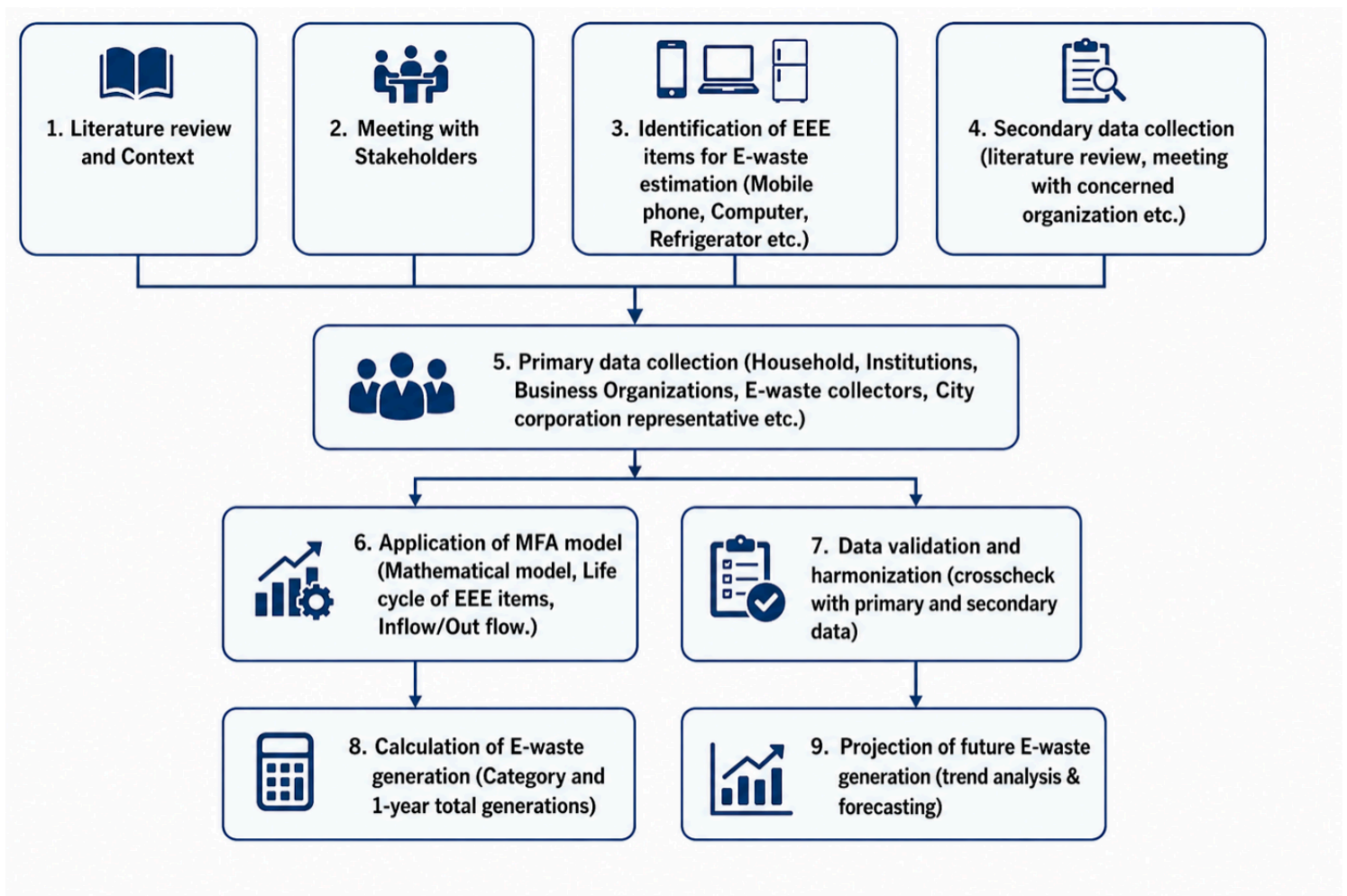


Figure 2

Methodological framework of E-waste generation

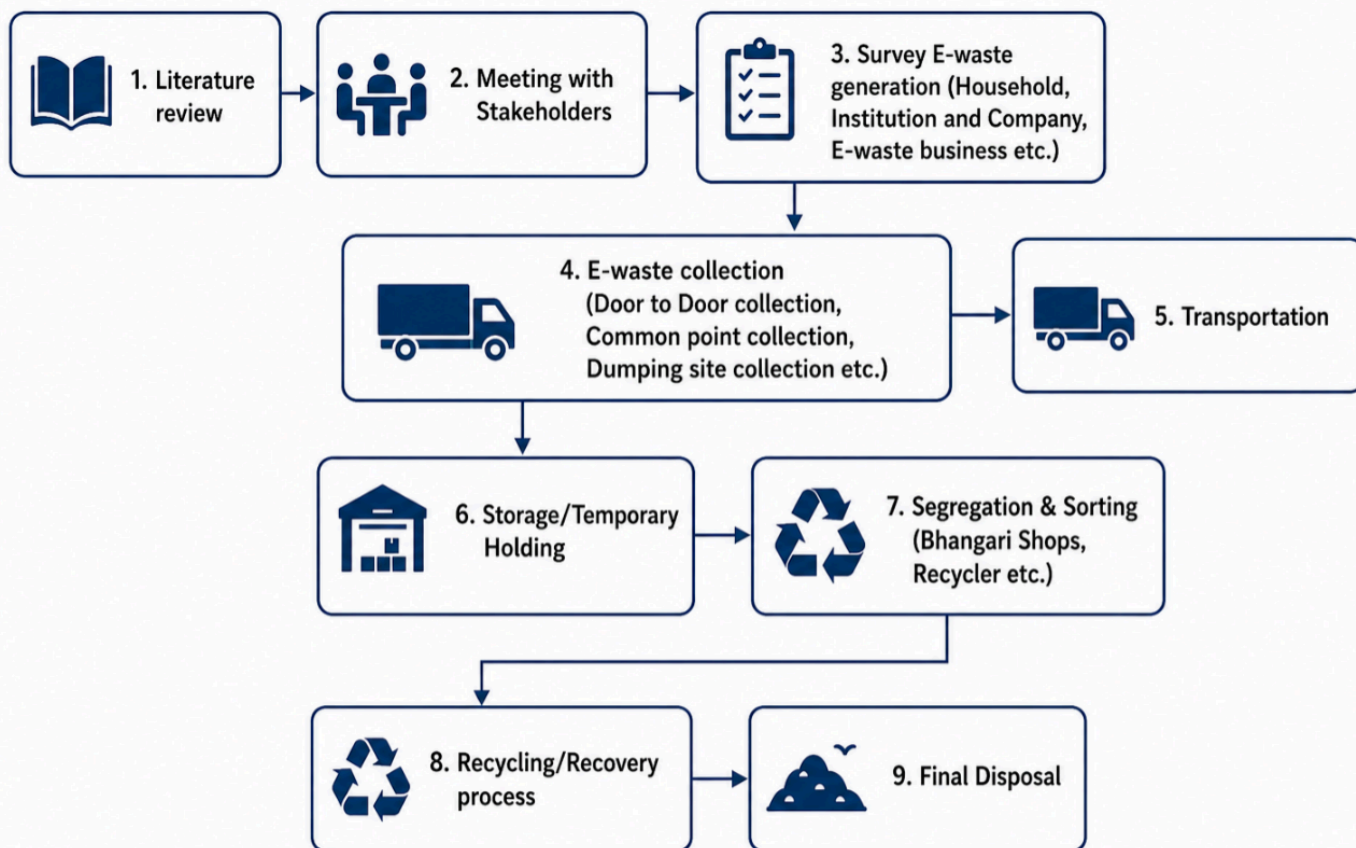


Figure 3

Assessment of the E-waste Management practices in Gazipur City Corporation

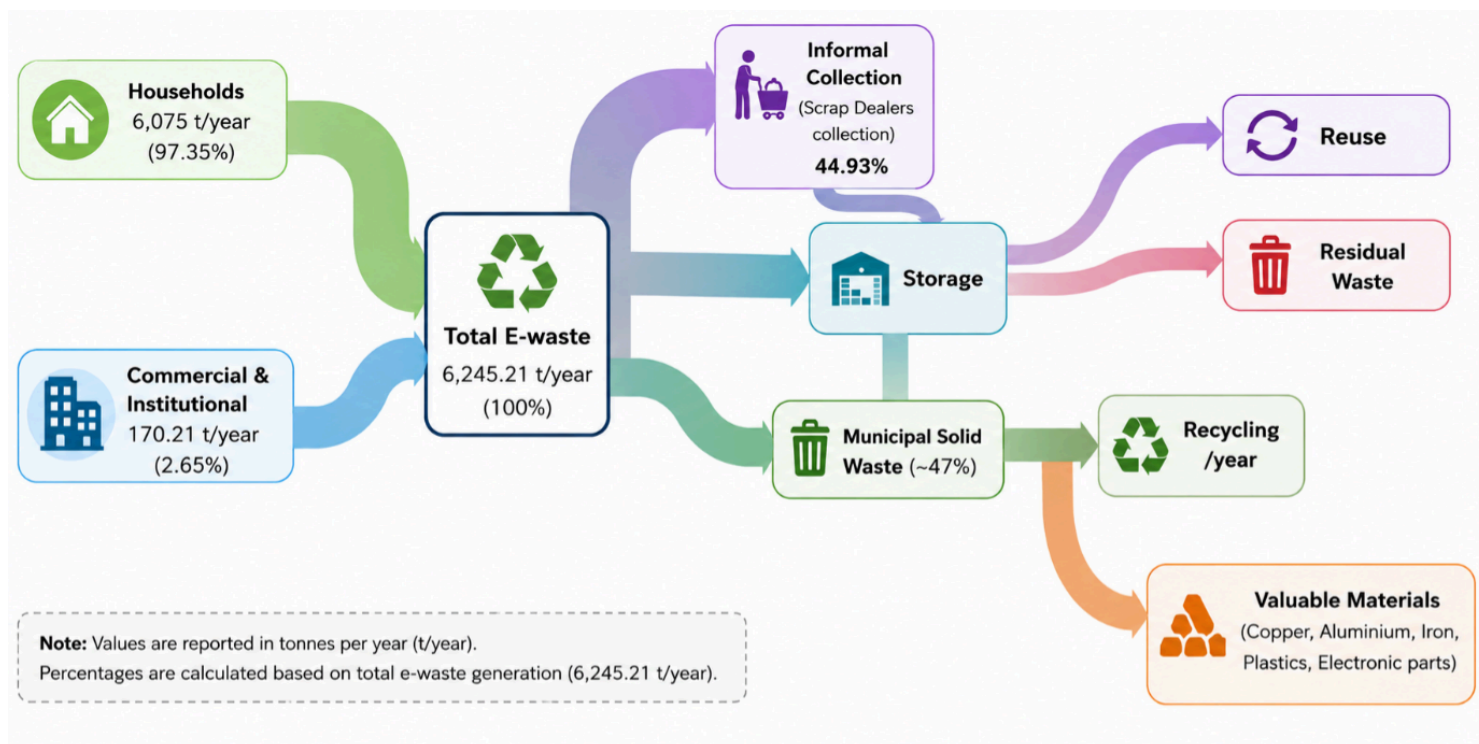


Figure 4

Sankey Diagram of E-waste Material Flow in Gazipur City Corporation (2024)