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# Material Flow Analysis of Waste Electrical and Electronic Equipment in Zamboanga City, Philippines: Current Practices and Future Opportunities

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## ABSTRACT

This study addresses Sustainable Development Goal 12, the management of materials that harm society and the environment. Material Flow Analysis (MFA) of the waste electrical and electronic equipment (WEEE) is are primary requirement for comprehensive monitoring and disposal of electronic waste. In Zamboanga City, Philippines, the collected waste electrical and electronic equipment (WEEE) for 2022 was analyzed and interpreted. The analysis is divided into four primary stages: recycling, disposal, reuse/resell, and storage. According to the findings, 20.02 tons of WEEE were produced, of which 8.01 tons were held, 5.01 tons were recycled or resold, 4.00 tons were reused, and 3.00 tons were disposed of. The composition study of a few chosen WEEE components, such as CPUs, monitors, and printers, reveals significant amounts of recoverable elements, such as iron, aluminum, copper, polymers, and circuit boards. Three types of devices had the highest material recovery efficiency: CPUs (97.607%), displays (91.853%), and printers (98.796%). The study highlights the hazards that informal WEEE processing poses to the environment and public health. It also advocates for regulation and the formal integration of informal sector operations into the WEEE management system. The suggestions include raising public awareness, investing in recycling infrastructure, and enhancing data collection. The study concludes that a comprehensive WEEE management plan supported by robust regulatory frameworks and investments in formal recycling facilities is necessary to balance Zamboanga City's economic interests, public health, and environmental protection.

## INTRODUCTION

One of the Sustainable Development Goals, specifically SDG 12.5, is to substantially reduce waste generation through prevention, reduction, recycling, and reuse. Addressing this goal is particularly relevant to managing waste electrical and electronic equipment (WEEE), a critical issue in the Philippines and many other developing nations. This challenge is especially pronounced in Zamboanga City, a significant metropolitan hub in the southern Philippines. This research fills these gaps by concentrating on data availability and incorporating informal practices into formal systems in Zamboanga City. Previous studies on WEEE management using Material Flow Analysis (MFA) frequently ignore uncertainty analysis, circular economy principles, non-OECD (Organization for Economic Cooperation and Development) contexts, and the informal sector (Yedla 2016, Islam & Huda 2019, Azizi et al. 2023). It will also investigate the absence of methodological innovation, the recommendations of inadequate strategies, the lack of economic evaluations of material recovery, and the disregard for hazardous substances. Analyzing the material flow and generation patterns of WEEE in the city is imperative to effectively create policies and infrastructure to handle this challenge (Azizi et al. 2023).

Material flow analysis (MFA) is a well-established technique for mapping waste stream formation, collection, and processing, including WEEE (Islam & Huda 2019, Rimantho et al. 2019, Azizi et al. 2023). Using this method, waste management professionals and policymakers can find areas for improvement and thoroughly grasp Zamboanga City's WEEE management situation (Kong et al. 2023, 2024). Although MFA has been used to evaluate WEEE problems in other Philippine locations, the particular socioeconomic characteristics of Zamboanga City, such as the rate of urbanization and the activities of the informal sector, necessitate a customized strategy that tackles specific inefficiencies in the local collection and processing systems. For instance, studies conducted in Jakarta, Indonesia, revealed that insufficient data on WEEE creation and material flows significantly hampered effective management (Rimantho et al. 2019). Similarly, the evaluation of India's e-waste market highlighted the need for stricter regulations alongside the prevalence of informal processing activities (Rauf 2024). Building on these findings, this study offers a thorough analysis of the WEEE material flows in Zamboanga City, along with practical suggestions for incorporating informal sector practices into official systems.

In Zamboanga City, the WEEE generation is influenced by several socioeconomic factors, such as urbanization, population expansion, and consumer behavior. Identifying the precise patterns and amounts of WEEE generated is the initial stage in creating a thorough management plan. Additionally, charting the city's WEEE collection, transportation, and processing routes will highlight gaps and inefficiencies in the current system (Erdiaw-Kwasie et al. 2024, Moradi et al. 2024). This study also fills the gap in the effects of informal processing activities on public health and environmental safety, a persistent problem in developing countries where unregulated practices predominate (Eckhardt & Kaifie 2024, Owusu-Sekyere et al. 2024). Designing regulations that incorporate these actors and encourage safer recycling practices would require understanding the scope and importance of the informal sector in Zamboanga City's WEEE management ecosystem (Kong et al. 2023, 2024).

Moreover, understanding the value and material composition of WEEE produced in the city can help design sustainable business models and incentives for formal recycling facilities (Osmani et al. 2021, Vishwakarma et al. 2022). Identifying economic opportunities through MFA and exploring resource recovery potential may encourage more significant investment in WEEE management infrastructure (Derks et al. 2024). By incorporating WEEE into municipal waste plans and fostering synergies that maximize current collection technologies, the findings contribute to broader initiatives to improve regional solid waste management (Rimantho et al. 2019). Thus, applying MFA in Zamboanga City provides insightful information for creating a comprehensive WEEE management strategy that balances environmental preservation, public health issues, and financial viability.

In summary, this study addresses the gaps in previous MFA applications by (i) providing comprehensive information on material flows unique to Zamboanga City. (ii) Making recommendations for methods to incorporate informal sector operations into official systems. (iii) Providing applicable policy suggestions based on regional circumstances. By filling in these gaps, this study will further contribute substantially to advancing sustainable WEEE management techniques in cities such as Zamboanga City.

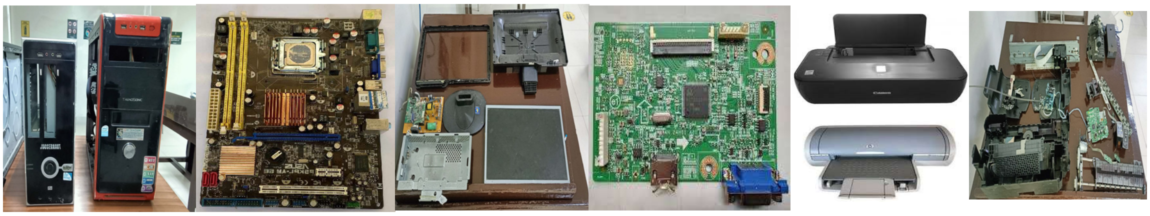
## MATERIALS AND METHODS

The examined WEEE components include various equipment, such as CPUs, monitors, and printers, shown in Fig. 1. These components were selected based on their prevalence in Zamboanga City's waste streams and their significant contribution to WEEE generation. The sampling process involved selecting representative items from major WEEE categories commonly disposed of in the offices and industries. The selection was not random but instead focused on capturing the primary waste streams reflective of the city's WEEE composition. Table 1 provides details of nine (9) sample data for these parts, including the sort, brand, year of purchase, year of disposal, and weight in kilos.

The study divided the process into four stages to analyze the material flow of WEEE, in Table 2: storage, reuse/resell, recycling, and disposal. The corresponding percentages of 40%, 20%, 15%, and 25% were based on the various WEEE

Table 1: Details of the WEEE samples.

| Item No. | Type | Brand | Year Acquired | Year Disposed | Weight (kg) |
|---|---|---|---|---|---|
| 1 | CPU | Asus | 2010 | 2016 | 3.13 |
| 2 | CPU | Asus | 2010 | 2016 | 3.97 |
| 3 | CPU | ECS | 2009 | 2016 | 5.33 |
| 4 | Monitor | BENQ | 2010 | 2016 | 2.36 |
| 5 | Monitor | AOC | 2010 | 2016 | 2.86 |
| 6 | Monitor | ACER | 2013 | 2017 | 2.43 |
| 7 | Printer | Canon | 2013 | 2016 | 3.31 |
| 8 | Printer | HP | 2013 | 2016 | 5.23 |
| 9 | Printer | Epson | 2017 | 2019 | 4.59 |



(a) CPU (b) Monitor (c) Printer

Fig. 1: WEEE samples obtained.

Table 2: Industry WEEE generated in 2022 (Kong et al. 2024).

| Industries in Zamboanga City | Storage 40% | Reuse/ Resell 25% | Recycling 20% | Disposal 15% | TONS |
|---|---|---|---|---|---|
| Telecommunication | 1.2 | 0.75 | 0.6 | 0.45 | 3 |
| Fish Canning and Fish Meal Plant (PSIC- 107) | 0.068 | 0.0425 | 0.034 | 0.0255 | 0.17 |
| Livestock Production (PSIC - 14) | 0.0006 | 0.000375 | 0.0003 | 0.000225 | 0.0015 |
| Production of Fishmeal for animal feed, Cold storage, preparation, and preservation of fish (Canning) | 0.8004 | 0.50025 | 0.4002 | 0.30015 | 2.001 |
| Manufacture of Ice (PSIC - 1079) | 0.0012 | 0.00075 | 0.0006 | 0.00045 | 0.003 |
| Beverage Manufacturing (PSIC -1104) | 0.0028 | 0.00175 | 0.0014 | 0.00105 | 0.007 |
| Financial Institution (PSIC - 55) | 0.00332 | 0.002075 | 0.00166 | 0.001245 | 0.0083 |
| Radio station | 5.84 | 3.65 | 2.92 | 2.19 | 14.6 |
| Real Estate Activity with owned or leased property | 0.00004 | 0.000025 | 0.00002 | 0.000015 | 0.0001 |
| Fuel Refilling Station | 0.00008 | 0.00005 | 0.00004 | 0.00003 | 0.0002 |
| Manufacturer/Exporter of Coconut Products | 0.052 | 0.0325 | 0.026 | 0.0195 | 0.13 |
| Oil Depot | 0.01 | 0.00625 | 0.005 | 0.00375 | 0.025 |
| Resort and other tourism/leisure projects | 0.01 | 0.00625 | 0.005 | 0.00375 | 0.025 |
| Product Merchant Wholesaler Industry | 0.0008 | 0.0005 | 0.0004 | 0.0003 | 0.002 |
| Wholesale of liquid and gaseous fuel products (PSIC - 46610) | 0.005 | 0.003125 | 0.0025 | 0.001875 | 0.0125 |
| 1. Sea Vessel Docking & Anchoring (Mooring and Anchoring); 2. Cater to Outbound and Inbound Passengers; 3. Cargo Handling, Stevedoring, and Storaging. (PSIC - 681) | 0.012 | 0.0075 | 0.006 | 0.0045 | 0.03 |
| Financial Institution | 0.0004 | 0.00025 | 0.0002 | 0.00015 | 0.001 |
| Hotel | 0.0024 | 0.0015 | 0.0012 | 0.0009 | 0.006 |
| **Total WEEE for 2022** | **8.0090** | **5.0057** | **4.0045** | **3.0034** | **20.0226** |

management practices disclosed by industry-specific surveys during focus group discussions in the prior study (Kong et al. 2024). Using the most recent official and statistical records available for that year, the analysis concentrated on data from 2022 of the DENR-EMB Region IX. The geographic scope was confined to Zamboanga City (EMB Region IX 2020, Jimenez 2022, Tolentino et al. 2023). Official records were sourced from government agencies, industry reports, and academic studies. Where data gaps existed, estimates were made based on similar studies conducted in comparable urban settings within the Philippines and Southeast Asia.

The information used in each step was from readily available records, and when needed, estimates were added to close any gaps or improve accuracy. Based on earlier research conducted in comparable contexts, the computations made assumptions about material recovery rates and disposal trends (Rimantho et al. 2019, Azizi et al. 2023). Uncertainties in the informal sector's contributions and industries' insufficient reporting were recognized as potential error margins. Cross-referencing several data sources helped to reduce these uncertainties and guarantee dependability.

The material composition and recovery efficiency were determined using the following formulas:

**Component Percent Weight Calculation**

$$\%\,Weight = \left(\frac{Weight\ of\ Component}{Total\ Weight}\right) x\ 100 \qquad \ldots(1)$$

**Total Weight Verification**

$$Total\ Weight = \sum(\text{Weights of All Components}) \quad \ldots(2)$$

**Efficiency Calculation**

$$Efficiency\ \% = \left(\frac{Total\ Weight\ of\ Recoverable\ Components}{Total\ Average\ Weight}\right) x\ 100 \quad \ldots(3)$$

This study offers a more thorough understanding of Zamboanga City's WEEE management system while acknowledging its limitations by addressing the gaps left by earlier research, such as the lack of data on activities in the informal sector.

## RESULTS AND DISCUSSION

Fig. 2 displays the Simplified Material Flow Analysis (MFA) of the Generation of Waste Electrical and Electronic Equipment (WEEE) in 2022. It provides an overview of the primary processes of handling trash and electronic equipment, such as generation, storage, recycling, reuse/resell, and disposal.

In 2022, 20.02 tons of waste electrical and electronic equipment (WEEE) were produced (Flow 1). This was stored in an estimated 8.01 tons (Flow 2), presumably for future repairs or reuse. An additional indication of efforts to extend the life cycle of products is the 5.01 tons of WEEE directed towards reuse or resale (Flow 3). Four tons of WEEE were recycled, contributing to resource recovery and waste reduction (Flow 4).

The entire waste management system of Zamboanga City is significantly impacted by the production of 20.02 t of WEEE. Although this may not seem significant, it indicates a growing waste stream that requires specialized handling and processing facilities, which must be covered for safety by the current municipal solid waste management plan. Zamboanga City's WEEE generation rate is comparatively moderate compared to Southeast Asian cities with comparable populations, such as Jakarta, Indonesia (Rimantho et al. 2019), where higher industrialization and consumption patterns have resulted in significantly higher rates. However, the majority of this waste is handled by the unorganized sector or ends up in landfills due to a lack of specialized WEEE processing facilities, thus posing risks to human health and the environment.

Analyzing the average weight and composition of a few WEEE components, such as CPUs, monitors, and printers, revealed significant differences in their material compositions and recovery efficiencies (Trad & Harb 2024). An overview of the WEEE findings in the samples is presented in Table 3. The following formulas were applied to comprehend the makeup and effectiveness of the material recovery:

**Component Percent Weight Calculation**

The weight of each component in the WEEE was either measured precisely or calculated using the following formula:

$$\%\ Weight = \left(\frac{Weight\ of\ Component}{Total\ Weight}\right) x\ 100 \quad \ldots(1)$$

For example, the weight of iron (Fe) in CPUs is calculated as

$$\%\ Weight\ of\ Iron\ (Fe) in\ CPUs = \left(\frac{8.132}{12.430}\right) x\ 100$$

$$= 65.72\%$$

**Total Weight Verification**

The total weight of each type of WEEE was verified by summing the weights of all individual com-

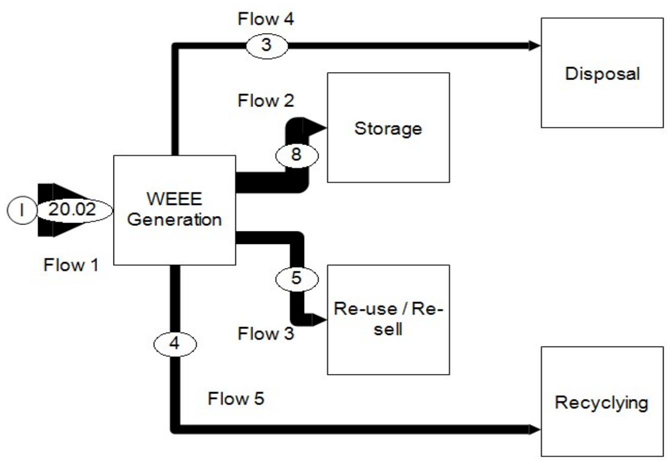



Fig. 2: Material flow analysis of WEEE Generation 2022.

ponents and comparing them with measured average weights.

$$Total\ Weight = \sum (\text{Weights of All Components}) \quad \ldots(2)$$

For example, for CPUs:

$$Total\ Weight\ of\ CPU\ components = \sum (8.132+0.524+0.575+1.543+1.273+0.024+0.024+0.004+0.035)=12.134$$

**Efficiency Calculation**

The efficiency of material recovery was calculated based on the proportion of the weight of the recoverable components to the total weight of the WEEE. The formula used is:

$$\text{Efficiency \%} = \left(\frac{Total\ Weight\ of\ Recoverable\ Components}{Total\ Average\ Weight}\right) x\ 100 \quad \ldots(3)$$

For example, for CPUs:

$$\%\ Efficiency\ of\ CPUs = \left(\frac{12.134}{12.430}\right) x\ 100 = 97.607\%$$

Table 3 summarizes the average weights of the CPUs, displays, and printers, which were 12.430, 7.650, and 13.130 kg, respectively. Printers had the most significant average weight, indicating that they could hold a sizable volume of material (Parthasarathy & Bulbule 2018, Islam & Huda 2019, Cho et al. 2024, Trad & Harb 2024). The graphical composition of the different WEEE types is shown in Fig. 3.

The following compositions were obtained:

**Iron (Fe):** CPUs had the highest iron content (8.132 kg), followed by printers (5.507 kg) and display devices (0.974 kg). The high iron concentration in these devices is most likely due to the large number of ferrous components used in the CPU manufacture.

**Aluminum (Al):** CPUs have a higher aluminum content (0.524 kg) than monitors (0.011 kg). The printers contained no observable metals.

**Copper (Cu):** Printers weighed the most at 0.683 kg, followed by CPUs at 0.575 kg, and monitors at 0.242 kg. Copper is widely used in wiring and in electrical components.

**Polymer:** Printers had the highest polymer content (6.050 kg), followed by CPUs (1.543 kg) and monitors (1.383 kg).

Table 3: Average weight and composition of the different WEEE.

| Component | CPU | Monitor | Printer | Key Findings/Implications |
|---|---|---|---|---|
| Average weight in kg | 12.430 | 7.650 | 13.130 | Highlights the potential material volume from each WEEE type; printers, being the heaviest, may offer greater resource recovery opportunities. |
| Iron (Fe) | 8.132 | 0.974 | 5.507 | High iron content in CPUs and printers indicates significant ferrous components, suggesting the need for efficient magnetic separation techniques during recycling. |
| Aluminum (Al) | 0.524 | 0.011 | - | Aluminum presence in CPUs suggests potential for aluminum recovery; monitors have negligible amounts. |
| Copper (Cu) | 0.575 | 0.242 | 0.683 | Copper is valuable and recoverable; its presence in all three WEEE types underscores the importance of targeted extraction methods. |
| Polymer | 1.543 | 1.383 | 6.050 | High polymer content, especially in printers, calls for improved plastic recycling strategies; separation and processing technologies should be enhanced. |
| Circuit Boards | 1.273 | 0.739 | 0.731 | Circuit boards contain valuable metals; their recovery requires specialized e-waste recycling facilities. |
| Processor | 0.024 | - | - | CPUs uniquely contain processors, indicating specific resource extraction opportunities. |
| Ceramic | 0.024 | 0.185 | - | Ceramic presence differs across WEEE types; monitors have higher ceramic content, requiring different handling approaches. |
| Lithium Battery | 0.004 | - | - | CPUs contain trace lithium batteries, necessitating safe handling and disposal protocols. |
| Phosphorus (P) | - | 0.001 | - | Monitors contain trace phosphorus, requiring specific disposal considerations. |
| $SiO_2$ (Silicon Dioxide or Silica) | - | 3.185 | - | Silicon dioxide is significant in monitors, suggesting potential for glass recycling initiatives. |
| Cables and Connectors | 0.035 | 0.307 | - | Cables and connectors in monitors highlight the need for effective wire separation techniques. |
| Efficiency | 97.607 | 91.853 | 98.796 | Monitors have a slightly lower recovery efficiency, indicating room for improvement; targeted strategies may include better sorting and dismantling processes. Printers and CPUs show high efficiency, demonstrating effective recycling practices. |

The high proportion of polymers in printers is most likely a result of the extensive use of plastics in their casings and other components.

**Circuit Boards:** The CPUs, monitors, and printers weighed 1.273, 0.739, and 0.731 kg, respectively. The circuit boards were relatively equal in weight across the three types of equipment. Circuit boards are necessary components of electrical devices.

**Specialized Components:** CPUs contain processors coupled with trace amounts of ceramic and lithium batteries, whereas monitors comprise ceramic and silica ($SiO_2$).

The highest material recovery efficiency was found in printers (98.796%), CPUs (97.607%), and monitors (91.853%). This demonstrates the potential for effective recycling and resource recovery from these components, although the lower efficiency of the monitors indicates that there is still space for improvement in the recovery process. The difficulty of disassembling monitor components, particularly LCD screens, the presence of dangerous substances such as mercury in older LCD models, and a lack of specialized recycling facilities that can effectively recover valuable materials from monitors are some of the reasons for the somewhat lower efficiency of monitors.

The informal sector is vital for WEEE management in Zamboanga City. Qualitative insights from industry-specific surveys reveal various WEEE management approaches and focus group discussions (FGDs). These conversations, which involved participants coded as Respondents 1–8, highlighted various WEEE disposal techniques. For instance, manufacturing stores produce hazardous waste, whereas the healthcare industry frequently recycles or resells materials (Kong et al. 2024).

Understanding the reasons for the storage of particular WEEE volumes in contrast to their recycling is a crucial component of an improved approach. According to stakeholder interviews by Kong et al. (2024), storage frequently occurs because of a lack of readily available recycling options and knowledge about appropriate disposal techniques or the perceived worth of potentially reusable components. Policy recommendations must go beyond general formalization to address this; they should concentrate on developing financial incentives for recycling, setting up easily accessible collection locations, and teaching unorganized workers how to disassemble and recover valuable materials safely.

In addition to stronger regulations to mitigate unlawful dumping, a standardized framework for policies and procedures is required to formalize the informal sector and enhance its environmental sustainability. Adding WEEE guidelines to the Zamboanga City Environment Code (E-Code) (Panlungsod 2019) is one practical step. To ensure that manufacturers take more responsibility for the end-of-life management of their products, these guidelines should encourage corporate and non-governmental cooperation and establish Extended Producer Responsibility (EPR) programs.

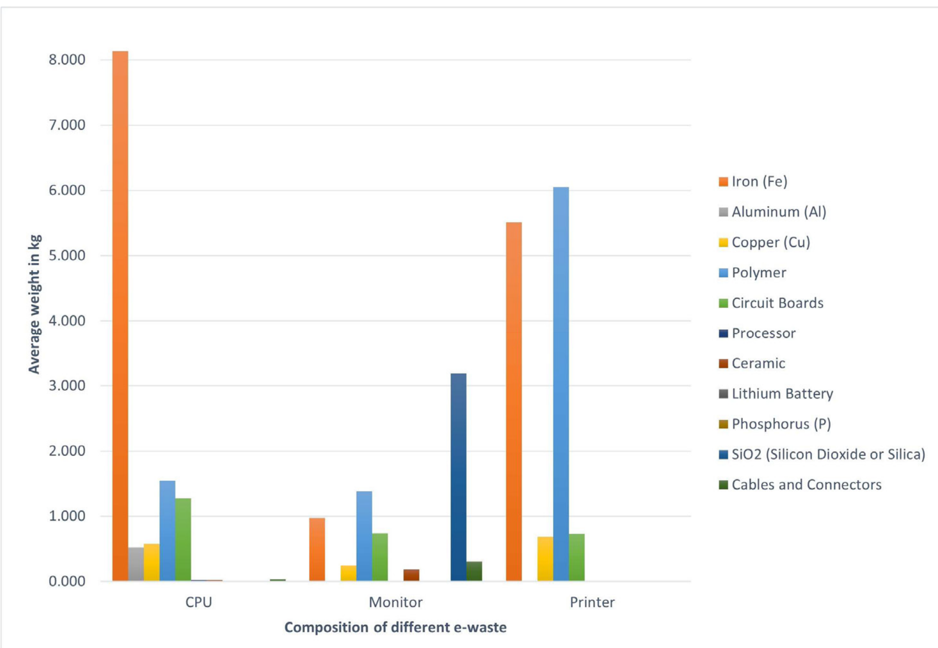



Fig. 3: Graphical composition of different WEEE.

Collaborative efforts with groups such as the Armed Forces of the Philippines (AFP) can enhance enforcement and logistical support.

Kong et al. (2024) emphasized the crucial role of community engagement, government collaboration, and public awareness. Providing training and equipment, setting up collection centers, forming alliances, launching awareness campaigns, and strictly enforcing environmental laws are essential components of an efficient framework for incorporating the unorganized sector into official WEEE management systems. Through the implementation of these measures and the amendment of the Environment Code, Zamboanga City (Panlungsod 2019) can establish a WEEE management system that is more equitable and sustainable, safeguarding the environment, promoting economic opportunities for informal workers, and protecting public health.

## CONCLUSIONS

A material flow analysis (MFA) study of waste electrical and electronic equipment (WEEE) in Zamboanga City comprehensively analyzed electronic waste creation, collection, and handling. According to the survey, the city produced approximately 20.02 tons of e-waste in 2022.

In summary, WEEE undergoes the following primary waste management processes, as shown in Fig. 2:

- 3.00 tons were disposed of
- 4.00 tons were recycled
- 5.01 tons were reused or resold
- 8.01 tons were stored.

Various recyclable elements were studied in the composition of some distinct WEEE components, including circuit boards, iron, aluminum, copper, monitors, and printers. In the survey, printers exhibited the best material recovery efficiency (98.796%), followed by CPUs (97.607 %) and displays (91.853 %). This implies that printers have great potential for resource recovery and the efficient recycling of these parts. Investment in the WEEE management industry can be stimulated by understanding WEEE's material composition and the economic value of WEEE, which offers substantial financial prospects for resource recovery and creates sustainable business plans for formal recycling facilities. The significance of informal WEEE processing operations in environmental degradation and health concerns is another noteworthy discovery (Andeobu et al. 2023, Abogunrin & Oladayo 2025). Regulatory frameworks must monitor these operations and include them in the official WEEE management systems. The report recommends expanding the collection of data on WEEE and material flows to improve management efficacy.

Furthermore, it encourages the regulation and formal system integration of activities carried out in the unofficial sector to improve recycling practices and reduce environmental and public health risks. Developing business strategies that capitalize on the economic potential of recoverable materials can increase revenues and boost productivity. Investing in formal recycling infrastructure is crucial. Public awareness and education are critical for encouraging responsible consumer behavior and facilitating the adoption of WEEE management policies. Policymakers should integrate the entire lifecycle of electronic products, from production to disposal, by developing and enforcing laws that promote environmentally friendly WEEE and Electronic Equipment management techniques. Changes to the Zamboanga City Environment Code (E-Code) are necessary. Previous studies have emphasized the importance of stakeholder collaboration, including working with the informal sector to address the challenges they encounter (Panlungsod 2019, Kong et al. 2024). The thematic analysis results suggest that this entails encouraging collaboration and moral leadership in all areas of WEEE management. As suggested by Zamboanga's Environment Code, infrastructure for managing WEEE should be invested in concurrently with other initiatives. To address the potential advantages of a standardized policy and procedure framework, this will strengthen waste management (Panlungsod 2019), encourage recycling and recovery at the barangay level, and create standardized frameworks. Public awareness campaigns should be organized as the next step, especially at the barangay level (Zamboanga City Local Sustainable Sanitation Plan Team 2021).Finally, enforcement measures must be implemented to reduce environmental and public health hazards. To manage WEEE, policymakers must guarantee collaboration between the public and the government.

The following action plans are required to improve WEEE management and promote a comprehensive approach in Zamboanga City: (1) foster stakeholder collaboration, which includes encouraging teamwork and ethical management across all sectors involved in WEEE management; (2) invest in infrastructure for handling WEEE, which incorporates standardized frameworks; (3) launch strong public awareness campaigns to educate consumers; and (4) implement strict enforcement measures to reduce environmental and public health risks.

The research findings simplify the understanding of Zamboanga City's WEEE management practices, which also offer insightful viewpoints that can be applied to similar global urban settings. This will serve as the basis for creating evidence-based policies that support ethical behavior, thereby aligning the economic, social, and environmental goals. Additionally, it is essential to conduct further research to improve regulations, incorporate data-gathering methods, and increase funding for recycling infrastructure as part of future efforts. Lastly, the aggregated data would help Zamboanga City manage WEEE to safeguard people, the environment, and sustainability.

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