

Original Research

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) are primary requirements 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.

1. 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 and Huda, 2019a; Azizi, Hanafiah and Woon, 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 creating policies and infrastructure to handle this challenge (Azizi, Hanafiah and Woon, 2023).

Material flow analysis (MFA) is a well-established technique for mapping waste stream formation, collection, and processing—including WEEE (Islam and Huda, 2019a; Rimantho, Noor and Effendi, 2019; Azizi, Hanafiah and Woon, 2023). Using this method, waste management professionals and policymakers can find areas for improvement and thoroughly grasp Zamboanga City's WEEE management situation (Kong, de los Reyes and Siacor, 2023; Kong, Siacor and Reyes, 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,

Noor and Effendi, 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, Abunyewah and Baah, 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 and 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, de los Reyes and Siacor, 2023; Kong, Siacor and Reyes, 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, Bidmon and Ciulli, 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, Noor and Effendi, 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.

2. MATERIALS AND METHODS

The examined WEEE components include various equipment, such as CPUs, monitors, and printers, shown in Figure 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 rep-

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.

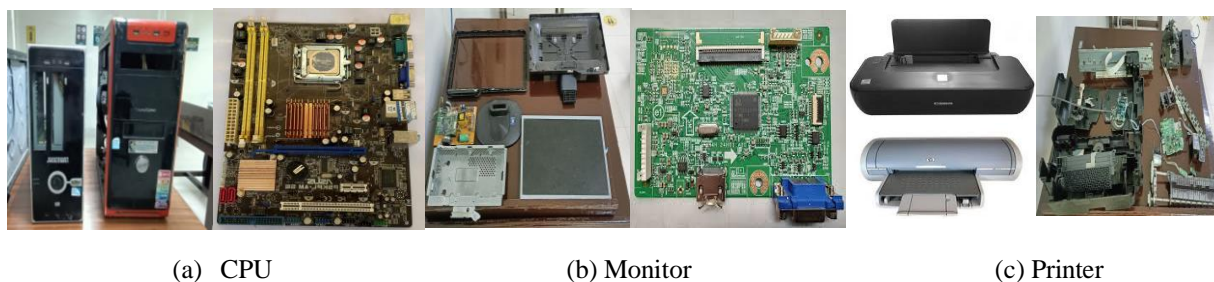


Fig. 1: WEEE samples obtained

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

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 management practices disclosed by industry-specific surveys during focus group discussions in the prior study (Kong, Siacor and Reyes, 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.

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 Storing. (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

Table 2: Industry WEEE generated in 2022 (Kong, Siacor and Reyes, 2024)

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, Noor and Effendi, 2019; Azizi, Hanafiah and Woon, 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:

2.1 Component Percent Weight Calculation

$$\% \text{ Weight} = \left(\frac{\text{Weight of Component}}{\text{Total Weight}} \right) \times 100 \quad \dots(1)$$

2.2 Total Weight Verification

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

2.3 Efficiency Calculation

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

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.

3. RESULTS AND DISCUSSION

Figure 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.

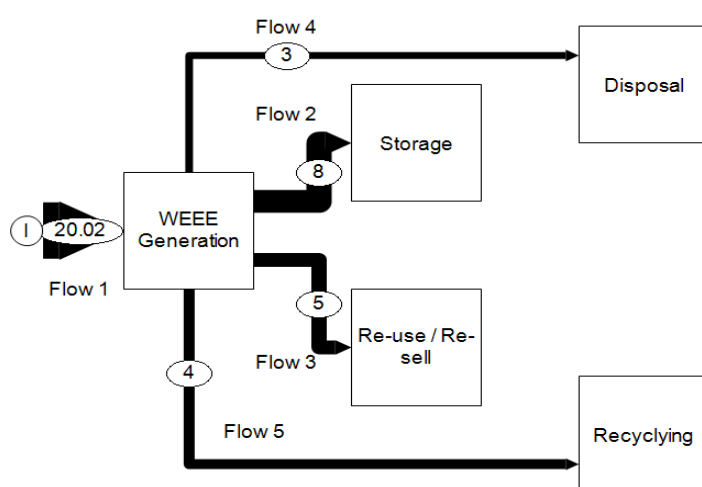


Fig. 2: Material flow analysis of WEEE Generation 2022

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 repair or reuse. An additional indication of efforts to extend the life cycles of products is the 5.01 tons of WEEE directed towards reuse or resale (Flow 3). Four tons of WEEE were recycled, contributing more 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 tons of WEEE. Nevertheless, it may not seem like much, but this 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 when compared to Southeast Asian cities with comparable populations, like Jakarta, Indonesia (Rimantho, Noor and Effendi, 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 material composition and recovery efficiency (Trad and Harb, 2024).

An overview of the WEEE findings in the sample is given in Table 3. The following formulas were applied to comprehend the make-up and effectiveness of material recovery:

3.1. Component Percent Weight Calculation

Each component's weight in the WEEE was either measured precisely or calculated using the following formula:

$$\% \text{ *Weight* } = \left(\frac{\text{Weight of Component}}{\text{Total Weight}} \right) \times 100 \quad \dots(1)$$

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

$$\% \text{ *Weight of Iron (Fe) in CPUs* } = \left(\frac{8.132}{12.430} \right) \times 100 = 65.72 \%$$

3.2. Total Weight Verification

The total weight for each type of WEEE is verified by summing the weights of all individual components and comparing it with the measured average weight.

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

For instance, for CPUs:

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

3.3. Efficiency Calculation

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

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

For example, for CPUs:

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

Table 3 summarizes the average weights of the CPUs, displays, and printers, which were found to be 12.430 kg, 7.650 kg, and 13.130 kg, respectively. Printers had the most significant average weight, indicating they

could hold a sizable volume of material (Parthasarathy, S and Bulbule, 2018; Islam and Huda, 2019b; Cho *et al.*, 2024; Trad and Harb, 2024). The graphical composition of the different WEEE is shown in Figure 3.

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.

Moreover, the following compositions were obtained:

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

Aluminum (Al): CPUs have a more extensive aluminum content (0.524 kg) than monitors (0.011 kg). Printers contained no observable metal.

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 electrical components.

Polymer: Printers had the most considerable polymer content (6.050 kg), followed by CPUs (1.543 kg) and monitors (1.383 kg). The high proportion of polymers in printers is most likely a result of the extensive usage of plastic in their casings and other components.

Circuit Boards: The CPUs weighed 1.273 kg, monitors 0.739 kilograms, and printers 0.731 kg. These circuit boards were relatively equal in weight across the three various types of equipment. Circuit boards are a necessary component of any electrical device.

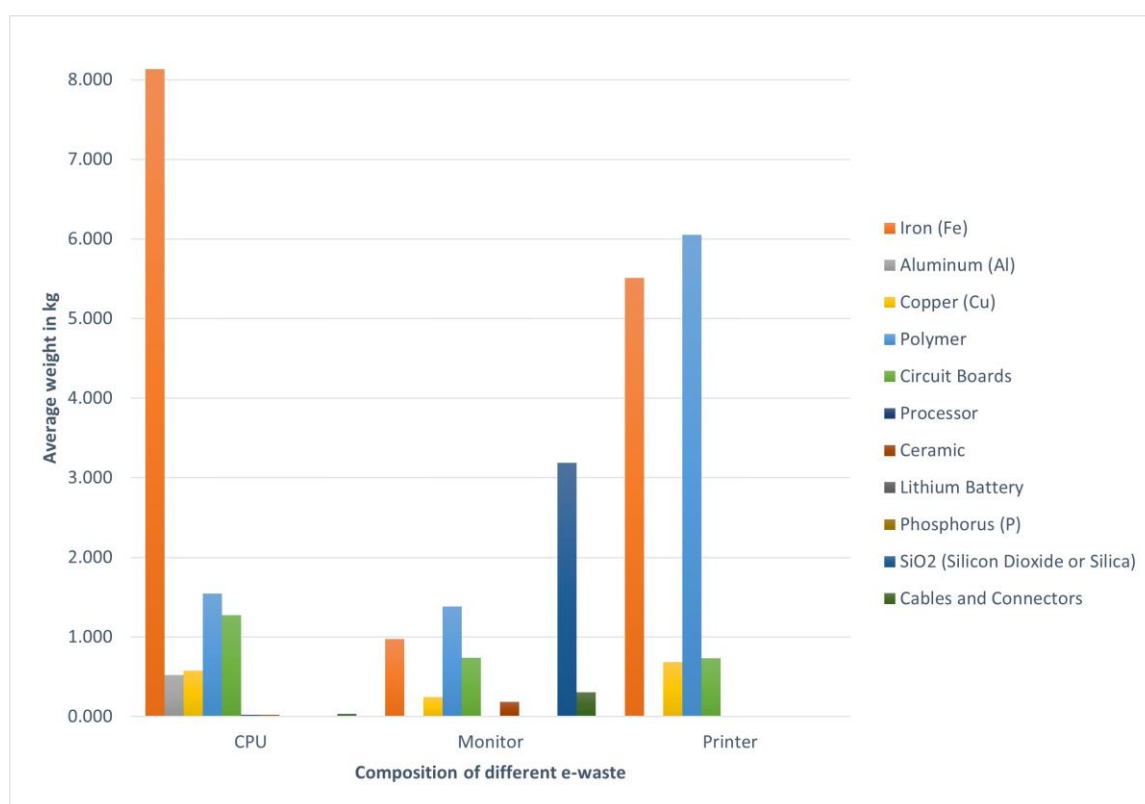


Fig. 3: Graphical composition of different WEEE

Specialized Components: CPUs contain processors coupled with trace amounts of ceramic and lithium batteries, while monitors comprise ceramic and silica (SiO₂).

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, even while the monitors' lower efficiency 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 like 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 to the WEEE management in Zamboanga City. Various WEEE management approaches are revealed by qualitative insights from industry-specific surveys and focus group discussions (FGDs). These conversations, which involved participants coded as Respondents 1 through 8, highlight various WEEE disposal techniques. For instance, manufacturing stores produce hazardous waste, while the healthcare industry frequently recycles or resells materials (Kong, Siacor and Reyes, 2024).

Understanding the reasons behind 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 happens 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 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. Collaborative efforts with groups like the Armed Forces of the Philippines (AFP) can enhance enforcement and logistical support even more.

The study by Kong et al. 2024 emphasizes 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 all 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.

4. CONCLUSIONS

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

In summary, the WEEE wastes go to the following primary waste management processes, as shown in Figure 2:

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

Various recyclable elements were in the composition study 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%), CPUs at 97.607%, and displays at 91.853%. This implies that printers have great potential for resource recovery and efficient recycling from these parts. Investment in the WEEE management industry can be stimulated by understanding WEEE's material composition and economic value, 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, Wibowo and Grandhi, 2023; Abogunrin and Oladayo, 2025). Regulatory frameworks must monitor these operations and include them in the official WEEE management system. The report recommends expanding the collection of data on WEEE and material flows to increase 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 hazards. Developing business strategies that capitalize on the economic potential of recoverable materials can increase revenue and boost productivity. Investing in formal recycling infrastructure is crucial. Public awareness and education efforts 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 management techniques. It was necessary to make changes to the Zamboanga City Environment Code (E-Code). Previous studies emphasized the importance of stakeholder collaboration, including working with the informal sector to address challenges they encounter (Panlungsod, 2019; Kong, Siacor and Reyes, 2024). According to the results of the thematic analysis, 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. 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 levels, 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). Lastly, enforcement measures must be implemented to lower environmental and public health hazards. To manage WEEE, policymakers must also 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 understanding 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 economic, social, and environmental goals. Additionally, it is essential to conduct more 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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