

Localized E-Waste Recycling Framework for General Santos City: A Circular Economy Approach

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Abstract. The global electronic waste (e-waste) challenge is particularly acute in urbanized cities like General Santos City, Philippines, due to inadequate infrastructure, weak legal frameworks, and a reliance on informal recycling practices. Despite global advancements in recycling technologies, localized, context-specific solutions for e-waste management remain a significant gap. This study utilizes Principal Component Analysis (PCA) and Semi-Partial Correlation Coefficients (SPCC) to examine e-waste categories and their recycling implications. PCA identifies Factor 1, including Temperature Exchange Equipment (TEE), Screens and monitors (S&M), and Small ICT devices (SICT), explaining 50.24% of the variance (eigenvalue = 3.014), driven by widespread ownership and common disposal patterns. Factor 2 (eigenvalue = 1.091) accounts for 18.18% of the variance, highlighting challenges in disposing of Large Electrical Equipment (LEE) and Lamps. The remaining factors (eigenvalues 0.618–0.266) emphasize the need for targeted recycling for Small Electrical Equipment (SEE) and emerging categories like medical devices, drones, and EV batteries. SPCC analysis further refines these findings, revealing a strong correlation ($r = 0.509$, $p < 0.001$) between TEE and S&M, suggesting that clustering these categories could optimize collection efforts. Moderate correlations were also found: ($r = 0.419$, $p < 0.001$) between SEE and LEE and ($r = 0.395$, $p < 0.001$) between SEE and SICT, indicating that material types and recycling convenience influence disposal practices. The weak correlation between Lamps and other categories ($r = 0.067$, $p > 0.05$) underscores the urgent need for specialized recycling solutions and establishing policy-driven collection points in high-traffic areas. This study strengthens e-waste management theory and provides a practical framework for enhancing collection systems, processing, and recycling systems, data monitoring and formalization of urban mining, and institutional mechanisms within a circular economy.

Keywords: Collection system; Data monitoring; Institutional mechanisms; Processing systems; Urban mining formalization.

1.0 Introduction

The evolution of information technology has made online communication indispensable for households, businesses, governments, schools, and religious organizations (O'Leary, 2020), revolutionizing interactions across cultures and societies (Borthakur & Singh, 2022). However, this digital transformation raises concerns over the growing use of Electrical and Electronic Equipment (EEE) and the increasing generation of e-waste (Forti et al., 2020). 2019 global e-waste generation reached 53.6 million metric tons, with only 17.4% adequately recycled. To visualize this, imagine 4.5 million garbage trucks filled with discarded electronics, enough to stretch halfway around the Earth. If piled to one meter, this e-waste would cover 53.6 square kilometers—roughly the size of Manhattan, New York, San Juan City, Metro Manila, or nearly half of Boracay Island. E-waste, accounting for just two percent of global solid waste, disproportionately contributes to hazardous waste in landfills, posing serious

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environmental and health risks (DENR, 2023). With annual growth of 3-5 percent, global e-waste could reach 76-88 million metric tons by 2030, wasting billions of dollars in valuable resources due to low recycling rates.

Herat (2021) highlighted that the Philippines generates 425,000 tons of e-waste annually, positioning it in the middle tier globally for e-waste generation. Regarding per capita e-waste, the Philippines surpasses neighboring Southeast Asian countries such as Bangladesh (1.2 kg) and Cambodia (1.1 kg). This increase is primarily driven by the increasing use of electronic devices and the limited recycling infrastructure in the country. Scholarly discussions highlight the dual nature of e-waste: a growing health and environmental crisis (Zhang et al., 2012; Hossain et al., 2015; Forti et al., 2020). Toxic chemicals from e-waste contaminate air, soil, and waterways, harming ecosystems and food supplies (Orisakwe et al., 2019). This impact is evident in communities near Ghana's Korle Lagoon and Pakistan's Lyari River, where pollution endangers aquatic life and livelihoods (Huang et al., 2014; Hameed et al., 2020). In General Santos City, a coastal urban area in Mindanao, e-waste mismanagement threatens Sarangani Bay, a critical fishing ground for thousands. Contamination disrupts its ecosystem, jeopardizing biodiversity, fisheries, and the economic well-being of nearby communities (Indab et al., 2003).

On the other hand, discarded electronics contain valuable materials like gold, silver, and rare earth elements that can be recovered through proper recycling processes (Cesaro et al., 2018). However, an alarming 86% — or 44.3 million metric tons — of global e-waste is either improperly discarded or left unaccounted for, resulting in the loss of valuable resources. This mismanagement directly undermines the economic potential of e-waste, which is estimated to contain raw materials worth approximately \$57 billion in 2019 (Forti et al., 2020). To address this issue, scholars propose adopting a Circular Economy approach, focusing on "urban mining" to maximize resource recovery (Hörtl et al., 2017; Azevedo et al., 2019; Debnath et al., 2022).

Amid escalating e-waste challenges, the Philippine government must adopt robust policies such as Extended Producer Responsibility (EPR), waste collection, recycling initiatives, and public sensitization (Kumar et al., 2017). While Republic Act 9003, the "Ecological Solid Waste Management Act of 2000," provides a foundation for waste management, its application to e-waste is technically inadequate and semantically vague (Carisma, 2009). The Act's primary focus on general solid waste and its vague categorization of "special waste" hinder precise e-waste measurement, especially in urban settings (Li et al., 2006). This issue is further exacerbated by the "invisible flow" of e-waste — exports from developed countries to the Philippines, a non-signatory to the Basel Ban, potentially turning the country into a dumping site (Lepawsky & McNabb, 2010; Bakhiyi et al., 2018). Insufficient monitoring of domestic e-waste intensifies the issue (Yang, 2020).

The weak public compliance with waste segregation and materials recovery in General Santos, especially regarding e-waste, highlights significant challenges in the city's waste management efforts. The absence of penalties or incentives for proper disposal leads to apathy towards practices like e-waste segregation, resulting in improper disposal, contamination of recyclables, and accumulation in landfills (Garcia, Marcilla, Flores & Lapong, 2024). E-waste, which contains hazardous materials, requires specialized handling, but without effective enforcement and infrastructure, people may resort to hazardous and inefficient *ad-hoc* disposal methods. To address this, the 10-Year Ecological Solid Waste Management Program must incorporate stronger regulations, public education, and penalties to ensure proper segregation and disposal (BIMP-EAGA, 2018) of both general and electronic waste.

While global advancements in recycling technologies offer promising solutions, localized frameworks tailored to regional conditions remain limited. Effective e-waste recycling requires addressing unique local challenges and optimizing opportunities. Literature highlights the potential of Principal Component Analysis and Semi-Partial Correlation Coefficients to reveal interdependencies among e-waste categories, identifying patterns that inform targeted recycling strategies. Understanding these relationships strengthens General Santos City's circular economy by identifying opportunities for material recovery, reuse, and waste reduction tailored to its specific waste profile and economic capacity. This approach ensures more efficient and sustainable recycling outcomes. This study aims to develop a localized framework for e-waste recycling to address gaps in infrastructure and policies in General Santos City.

2.0 Methodology

2.1 Research Design

This study adopts a correlational descriptive research design, integrating multivariate analysis, to investigate the relationship between e-waste disposal practices across six categories of electronic and electrical equipment (EEE) and their impact on the waste diversion goals of General Santos City. Principal Component Analysis (PCA) was employed to distill complex data and highlight key factors influencing disposal behaviors, while semi-partial correlation analysis (SPCC) isolated the individual contributions of variables. PCA reduced data dimensionality by grouping correlated variables, while SPCC clarified direct relationships between e-waste categories and disposal behaviors, isolating confounding effects. This comprehensive analytical approach, grounded in the 3R hierarchy framework for e-waste disposal practice outlined by Blake (2018), provides refined insights into the key drivers of e-waste management. It offers actionable, context-specific recommendations to enhance local recycling programs and promote sustainable waste diversion efforts.

2.2 Research Locale

General Santos City (Gensan), known as the "Tuna Capital of the Philippines," faces substantial challenges in municipal solid waste management. The City Waste Management Office (CWMO) oversees the collection, segregation, and processing of various waste types, including food scraps, plastics, and paper, disposed of in the city's landfill. Gensan generates around 300 tons of waste daily, with a per capita generation rate of 0.289 kilograms. However, the city's collection efficiency is limited to 45%, with only 80–90 tons transported to the 64-hectare landfill in Barangay Sinawal. The solid waste sector contributes significantly to the city's environmental impact, accounting for 76% of its total greenhouse gas emissions, estimated at 54,662.16 tCO₂e. Despite a 53% waste diversion rate, approximately 60,162.8 metric tons of waste still end up in landfills annually (BIMP-EAGA, 2018). Building on the work of Garcia et al. (2024), this study focuses on the same five barangays – Dadiangas North, Dadiangas East, Dadiangas West, Dadiangas South, and Lagao (NEWS-L) – to explore how e-waste disposal practices intersect with the city's existing waste management infrastructure. This continuity strengthens the research's relevance and adds longitudinal significance, providing deeper insights into the evolving dynamics of waste management in Gensan.

2.3 Research Participants

This study utilizes the same sample of 102 participants from General Santos City as Garcia et al. (2024) to ensure consistency with the original research. It extends the previous work by examining the relationship between e-waste disposal practices across different EEE categories and the effectiveness of local e-waste management systems. Given the continuing e-waste challenges in the community, the sample remains relevant. While the original study focused on awareness-behavior gaps, this research explores the impact of disposal practices on local infrastructure. It investigates how to transform current challenges into opportunities for improvement – areas not fully addressed in the prior study. The sampling plan follows a multi-stage hybrid methodology combining stratified and proportionate probability sampling to ensure consistency. Participants are drawn from three strata: Household-Level Consumers (HHCs), Commercial-Level Consumers (CLCs), and Consumers from Educational Institutions (CEIs), with a proportionate allocation based on each group's contribution to e-waste generation.

2.4 Research Instrument

This novel study builds upon the instrument employed in our previous research (Garcia et al., 2024), which explored the cognitive and affective factors influencing e-waste disposal practices. In the previous study, we asked participants to account for their e-waste disposal practices across six electrical and electronic equipment (EEE) categories. These practices, aligned with the 3R hierarchy of e-waste management, included discarding and ordinary waste, hoarding, reclaiming functional parts, repairing, recycling, selling, and donating (Blake, 2018), providing a comprehensive understanding of disposal behaviors within each EEE category.

2.5 Data Gathering Procedure

The present study used the existing data from Garcia et al. (2024) to analyze how disposal practices align with the 3R hierarchy of e-waste management outlined by Blake (2018). Based on the literature, we developed a seven-level disposal practices spectrum that categorizes disposal behaviors in increasing order of sustainability, ranging from the least sustainable (level 1) to the most sustainable (level 7), creating a comprehensive continuum.

Donation is a top reuse strategy within the spectrum, giving electronics a second life. Selling follows, allowing devices or parts to be exchanged for money and promoting resource conservation. Recycling recovers valuable materials like metals and rare earth elements, reducing the need for virgin resources and minimizing environmental harm (Zeng et al., 2018). Recovery extracts materials from e-waste that cannot be recycled, playing a key role in resource preservation. Repair extends the life of devices by restoring functionality. Hoarding and storing old electronics instead of disposing of them delays recycling or reuse. Finally, disposal is a last resort, with e-waste often mixed with regular waste, posing significant environmental risks.

We imported the detailed dataset from the previous study into Jamovi, an open-source software known for its robust capabilities in performing both univariate and multivariate analyses (Şahin & Aybek, 2019). To uncover patterns and reduce the complexity of the data, we applied Principal Component Analysis (PCA). Bartlett's Test confirmed the presence of significant relationships ($\chi^2 = 108$, $df = 15$, $p < .001$), supporting the use of multivariate analysis. Hence, to further refine the PCA results, we utilized Semi-Partial Correlation Coefficients (SPCC) to clarify the direct relationships between the variables and the identified principal components (Abdi, 2007).

2.6 Ethical Considerations

The study adhered to ethics approval no. 189-2024-MSUGSC-IERC from the Mindanao State University (MSU) Institutional Ethics Review Committee (IERC). The committee classified the research instrument as non-sensitive and ensured participant anonymity in compliance with the Data Privacy Act 2012.

3.0 Results and Discussion

3.1 Analysis and Implications of EEE Diffusion Rates

The Prevalence of Electronic and Electrical Devices: Exploring E-Waste Scenarios

The EU 2012/19 Directive defines e-waste as electrically or electronically powered equipment no longer in use, categorized into six groups (Baldé et al., 2015), each presenting unique challenges in disposal and recycling. Table 1 illustrates the percentage of each consumer segment (stratum) using various types of EEE, including Temporary Exchange Equipment (TEE), Screens and monitors (S&M), Lamps, Large EEE (LEE), Small EEE (SEE), and Small ICT Equipment (SICT). The data highlights high penetration rates across all segments, showing widespread usage. TEE and SICT items, such as air conditioners, refrigerators, smartphones, and laptops, have near-universal adoption with a 98% penetration rate. Lamps exhibit 100% penetration, emphasizing their ubiquity in residential, commercial, and educational settings. SEE appliances, like electric fans and irons, show 93% penetration. S&M items (e.g., TVs) have a lower commercial penetration (79%) but higher usage in households and educational institutions. LEE items, such as washing machines and photocopiers, exhibit higher penetration in households (77%) than in the commercial sector (68%), with educational institutions leading at 86%.

Table 1. EEE penetration rates by segment

Stratum	TEE	S&M	Lamps	LEE	SEE	SICT
Commercial	98%	79%	100%	68%	90%	100%
Schools	100%	100%	100%	86%	100%	100%
Households	97%	85%	100%	77%	90%	95%

The Rising Tide of E-Waste: Challenges and Opportunities in Sustainable Management

As the Philippine economy grows, the adoption of electric appliances follows a predictable pattern, with households initially prioritizing essential items for lighting (Lamps) and television sets (S&M). As incomes rise, families invest in essential but costly appliances like refrigerators (TEE), crucial for food preservation, while washing machines (LEE) are adopted later, often seen as luxury items in rural areas where manual laundry persists (McNeil & Letschert, 2010). The increasing use of small household appliances and ICT gadgets, including mobile phones, laptops, and air conditioning units (TEE), further exacerbates e-waste issues in the country. The widespread reliance on electronics for communication and internet access (Albert et al., 2021) and the growing popularity of energy-intensive items like air conditioning due to rising incomes and temperatures intensify the challenge. However, the Philippines faces inadequate e-waste management infrastructure and regulations, heightening environmental and health risks (Oteng-Ababio, 2012; Baldé et al., 2017). As the volume of e-waste rises, adopting sustainable disposal practices and effective recycling strategies is crucial. The following discussion examines EEE categories, disposal methods, and opportunities for improving sustainable e-waste management practices.

Disposal Practices for Temperature Exchange Equipment (TEE)

This category includes refrigerators, air conditioners, heat pumps, freezers, and dehumidifiers. These items are significant because they often contain hazardous refrigerants like Chlorofluorocarbons (CFCs) and Hydrochlorofluorocarbons (HCFCs), which can cause significant environmental harm if improperly disposed of (Benhadid-Dib & Benzaoui, 2012). The average lifespan of everyday TEE is around 10-15 years for refrigerators and air conditioners (Ikhlayel, 2016). The data shows that repair is the most common TEE disposal method among commercial, educational, and household consumers, with mean scores of 4.03 to 4.61, reflecting moderate pro-environmental practices. However, improvement is needed to achieve higher sustainability levels, like recycling or donating. Low standard deviations (1.33–1.48) indicate moderate variation within sectors.

Disposal and Management of Waste Screens and Monitors (S&M)

This category includes Cathode Ray Tube (CRT) monitors, flat-screen TVs, LCD monitors, and LED monitors. CRTs, used in older televisions and monitors, contain lead and cadmium, which are toxic. These items require special handling to avoid releasing these harmful substances (Cenci, Dal Berto, Schneider, & Veit, 2020). LCD and LED screens also pose risks due to mercury content, necessitating proper recycling processes. These items typically have an average lifecycle of 2–5 years (Kahhat & Williams, 2012). Educational institutions (mean = 4.50) excel in eco-friendly disposal, surpassing households (4.03). This aligns with the findings of Solé et al. (2012), which highlight the role of educational institutions as key societal influencers in fostering a foundational understanding and awareness of e-waste issues. Meanwhile, households exhibit the highest inconsistency (SD = 2.15), indicating diverse disposal practices.

Disposal Trends for Lamps

Lamps, including fluorescent and LED lights, pose recycling challenges due to their small size, complex materials, and toxic elements (EPA, n.d.). Though less hazardous, Halogen lamps require separate handling to recover valuable metals like tungsten or molybdenum. Lamp lifecycles vary: incandescent lamps last 1,000–2,000 hours, halogen lamps 2,000–4,000 hours, fluorescent lamps 8,000–10,000 hours, and LEDs 25,000–50,000 hours. Data from General Santos City shows diverse disposal practices. Households, with a mean score of 1.28, often discard lamps with regular waste, while educational institutions score 3.77, reflecting more responsible practices ranging from reclaiming to repairing. Commercial establishments score 2.88, indicating mixed disposal practices, with a particular tendency toward hoarding and reclaiming reusable parts. Despite the ubiquity of lighting goods, disposal habits exhibit significant variability, as reflected in standard deviations ranging from 0.999 to 2.20.

Challenges in Disposing of Large Appliances

This category includes large household appliances such as washing machines, stoves, dishwashers, microwaves, dryers, and ovens. While their size complicates recycling, proper separation makes material processing more efficient. The lifespan of these appliances varies depending on usage, quality, and environmental factors. Washing machines typically last 10-15 years, while stoves and ovens have a longer lifespan of 10-20 years. Descriptive statistics show that educational institutions lead in managing large appliances (mean = 4.59), particularly in repair and recycling, with relatively low variability (SD = 1.26). This suggests that educational institutions have more consistent practices in these areas. In comparison, residential consumers follow closely (mean = 4.48), focusing primarily on repair, but exhibit higher variability (SD = 1.82), indicating less consistency in their disposal practices. Commercial establishments trail behind (mean = 3.62), emphasizing reclamation and repair over recycling, and also show significant variability (SD = 1.66), reflecting inconsistencies in their e-waste management efforts.

Recycling Challenges of Small Household EEEs

Small electrical equipment, such as toasters, irons, blenders, and vacuum cleaners, are widely used in homes, offices, and institutions. While consuming less power than larger appliances, these items require careful recycling due to the materials they contain (Perkins et al., 2014). Their lifecycles vary from 5 to 15 years: toasters and irons last 5–7 years, while microwaves and vacuum cleaners average 8–12 years (Kahhat et al., 2008). Disposal data shows strong repair practices across sectors, with scores of 4.26 to 4.39. Educational institutions exhibit the most consistent behavior (SD = 1.45), reflecting structured approaches, while the residential sector has more significant variability (SD = 2.00). This inconsistency may result from differences in awareness, facility access, or habits,

emphasizing the need for targeted strategies to promote responsible disposal practices, particularly among households.

Vast Complexities in Small ICT Equipment (SICT)

SICT equipment like mobile phones, laptops, and tablets poses recycling challenges due to compact sizes, intricate designs, and valuable metals such as gold and copper (Vishwakarma et al., 2022). With a 1 to 5 years lifespan, these devices are often replaced due to rapid technological advancements and planned obsolescence (Kahhat et al., 2008; Gecit, 2020). Disposal practices vary across sectors in General Santos City: educational institutions lead in repair and recycling efforts (mean = 4.91, SD = 1.41). The commercial sector follows with moderate consistency (mean = 4.68, SD = 1.62), while households exhibit more significant inconsistency (SD = 1.83), often leaning toward repairing broken devices (mean = 4.41). Amid rapid urbanization, the volume of e-waste is steadily increasing, necessitating an upgrade to the local government's Centralized Materials Recovery Facility (CMRF) to manage the complexity of electronic waste effectively. E-waste segregation in the city must focus on key considerations that ensure proper disposal and facilitate the recovery of valuable resources and the safe handling of harmful substances.

Size and Bulk

The size and bulk of e-waste are significant considerations when developing a waste management system (Kahhat & Williams, 2009). Large and bulky items, like refrigerators, air conditioners, and washing machines, require specialized facilities to handle their bulk and ensure that materials such as steel, aluminum, and copper are recovered efficiently. These items should be segregated early in the collection process to prevent contamination with smaller devices and ensure the safe extraction of valuable materials. Non-hazardous components, such as plastics and metals from smaller appliances like toasters and radios, must be separated from hazardous items like batteries, CRT monitors, and fluorescent lamps containing mercury, lead, and cadmium. General Santos' CMRF must include dedicated areas for hazardous materials to prevent harmful exposure or environmental contamination.

Non-hazardous vs. Hazardous Components

As Perkins et al. (2014) noted, a key element of e-waste segregation is identifying hazardous components that pose significant risks to human health and the environment. Items containing harmful materials, such as mercury, lead, and cadmium—typically found in batteries, CRT monitors, and fluorescent lamps—must be carefully separated from non-hazardous components like plastics, metals, and circuit boards. The non-hazardous materials can generally be recycled, reducing the overall environmental impact of e-waste.

Recyclability and Material Recovery

The recyclability of different components plays a crucial role in the e-waste segregation process. Items like printed circuit boards (PCBs) in computers and mobile phones contain valuable metals such as gold, silver, and copper. These components should be carefully segregated for specialized recovery processes (Baldé et al., 2015). Additionally, wires and cables from devices like televisions, laptops, and washing machines should be separated to recover metals, particularly copper, which is highly valuable in recycling. Focusing on material recovery not only prevents waste but also helps reduce the demand for raw materials, which has economic and environmental advantages.

Functionality

Not all e-waste needs to be recycled—some items can still be used. Functional or reusable electronic devices, such as old mobile phones, laptops, or printers, can often be refurbished and reused, extending their life cycle and reducing the pressure on recycling systems (Baldé et al., 2015; Gecit, 2020). Segregating functional items from non-functional or obsolete ones is essential in promoting reuse. These items can be donated, sold, or refurbished, offering a second life to equipment with value. This practice reduces the need for immediate recycling and supports sustainable consumption by encouraging the repair and reuse of electronic devices. It further aligns with circular economy principles, where products are used for as long as possible before being recycled or disposed of.

Energy Storage

Batteries, capacitors, and power banks are standard in some Small EEE and many items under the Small ICT (SICT) category. However, these items contain potentially hazardous chemicals such as lithium, cobalt, and nickel, which require distinct handling and specialized recycling processes. Batteries, for instance, can leak harmful substances if improperly disposed of or handled, leading to environmental contamination. Authors such as Perkins et al. (2014) and Gecit (2020) suggest that energy storage devices should be segregated from other e-waste categories and processed separately to mitigate this risk. Specialized collection systems are needed to handle these items safely, ensuring that dangerous substances are contained and the valuable metals within these devices are recovered.

3.2 Analyzing the Spread of Disposal Practices Across EEE Categories

Urban E-Waste Disposal Trends: Bridging Behaviors and Infrastructure Gaps

Figure 1 provides practical insights into e-waste management practices in General Santos City, highlighting key challenges and opportunities for improvement. Based on the density distribution and the associated skewness and kurtosis values, TEE and LEE categories show similarities in their disposal patterns. Both categories have relatively low skewness (-0.0579 for TEE and -0.0888 for LEE), suggesting that their disposal behaviors are more evenly distributed across various disposal methods, such as recycling, selling, and repairing. These practices are aligned with the 3R hierarchy of conserving resources, reducing waste, and minimizing the environmental impact of manufacturing new products (Blake, 2018).

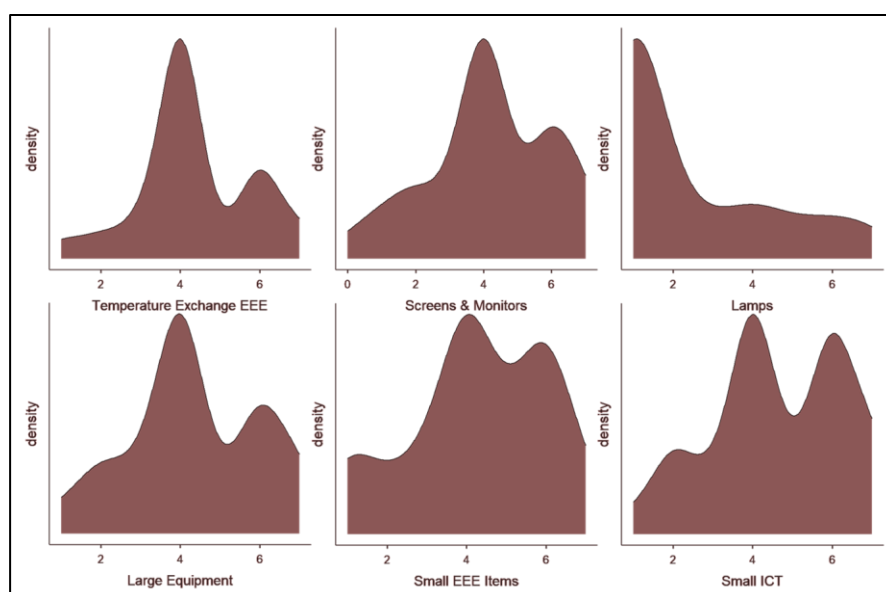


Figure 1. Density distribution of disposal practices across six EEE categories

Sectoral Variations and Sustainability Challenges

Efforts to extend the lifespan of appliances like refrigerators, air conditioners, and washing machines align with sustainable consumption principles (Mashhadi et al., 2016). These practices reflect local cultural values of thrift and "Pinoy (Filipino) Ingenuity," seen in widespread do-it-yourself (DIY) repairs and repurposing of electronics reported by the respondents. For lower-income residents, such approaches offer a cost-effective alternative to purchasing new items, blending financial practicality with environmental sustainability (Bovea et al., 2020). In contrast, the Screens & Monitors (S&M) and Small ICT (SICT) categories exhibit more significant negative skewness (-0.351 for S&M, -0.315 for SICT), indicating a higher tendency to hoard or reclaim valuable materials, prioritizing material recovery over more sustainable disposal methods.

Households (skewness of 0.193) and the commercial sector (skewness of -0.127) show more significant variability in e-waste disposal, with inconsistent behaviors across sectors. Negative kurtosis values, particularly in educational institutions (-0.422), point to significant hoarding, especially of items like monitors, mobile phones, and some appliances, often kept for sentimental value (Wakolbinger et al., 2014), potential future use (Esenduran

et al., 2019), or lack of recycling awareness (Wilkinson & Williams, 2020). Hoarding of e-waste delays recycling processes and exacerbates environmental waste, as valuable materials remain unused and hazardous components continue to pose environmental risks (Kahhat & Williams, 2012). Lamps, with the highest skewness (1.08), are improperly disposed of, likely due to inadequate infrastructure and awareness, necessitating a separate management approach.

Huisman et al. (2019, Part I) argue that the effectiveness of e-waste management is shaped by local infrastructure and consumer behavior. They emphasize that the availability of collection points, recycling facilities, and consumer awareness influences sector-specific disposal practices. Inadequate infrastructure and education lead to inconsistent disposal behaviors, hindering effective recycling. The authors advocate for tailored solutions addressing local contexts and sectoral needs. However, these findings overlook complexities in General Santos City, where sector-specific variations in disposal practices may reveal additional challenges. Hence, the current data does not fully capture these differences. To address this gap, Principal Component Analysis (PCA) can uncover relationships between variables and provide deeper insights into consumer behaviors. Bartlett's Test ($\chi^2 = 108$, $df = 15$, $p < .001$) supports the use of factor analysis, rejecting the null hypothesis that the variables are uncorrelated (Bartlett, 1950).

3.2 Multivariate Analysis of E-Waste Disposal Trends

Identifying Key Patterns for Optimized Management: A Principal Component Analysis

We conducted a Principal Component Analysis (PCA) using six e-waste categories, chosen for their relevance to e-waste flows and their impact on recycling, collection, and disposal. PCA helped identify patterns and reduce data dimensionality, grouping categories with similar characteristics for more efficient processing. Integrating the findings from the factor analysis and the density distribution analysis, we can understand e-waste disposal behaviors comprehensively and their implications for future waste management strategies. Table 2 below presents the eigenvalues and variance percentages for Factors 1 through 6, indicating the key categories that exhibit strong correlations and require targeted recycling strategies.

Table 2. *Summary of factor analysis for disposal trends*

Component	Eigenvalue	% of Variance	Cumulative %
1	3.014	50.24	50.2
2	1.091	18.18	68.4
3	0.618	10.30	78.7
4	0.547	9.11	87.8
5	0.464	7.74	95.6
6	0.266	4.43	100.0

Factor 1: TEE, S&M, and SICT (High-Priority Categories)

This factor includes large appliances like air conditioners, refrigerators (TEE), and screens and monitors (S&M), which contain hazardous materials like mercury and lead and require specialized recycling. The high penetration rate of temperature exchange equipment, screens and monitors, and small ICT devices in households, businesses, and educational institutions in General Santos reflects a significant accumulation of e-waste across these sectors. While consumers may engage in responsible disposal practices, such as recycling or repair, these products' complexity and environmental risks highlight the need for robust local infrastructure to manage their recycling and mitigate potential impact effectively.

Factor 2: LEE and Lamps (Large Appliances and Hazardous Components)

This category includes larger appliances like washing machines, microwave ovens, and lamps containing hazardous substances. While LEE items have a lower penetration rate than lamps, they present disposal challenges due to size and hazardous chemicals like mercury. The density distribution analysis shows that improper disposal practices for LEE and lamps are standard. Specialized infrastructure and policies are needed to dispose of these items, with dedicated recycling zones to recover valuable materials like copper and aluminum while safely handling hazardous components like capacitors.

Factor 3: SEE (Small Appliances and Audio Equipment)

Small appliances like toasters, radios, and speakers fall under this category. The widespread prevalence of Small Electrical Equipment (SEE) is often accompanied by improper disposal or hoarding once these items are no longer

functional. Due to their compact size, consumers may not prioritize proper disposal practices (Garcia et al., 2024). These items contain valuable materials that should be recycled, and awareness campaigns promoting the recyclability of small appliances and refurbishment and resale opportunities should be prioritized.

Factors 4 and 5: Niche and Emerging E-Waste Categories

This category includes niche items like medical equipment, smartphones, drones, and electric vehicle (EV) batteries, which contain rare or hazardous materials like mercury and lithium. Disposal practices for these high-penetration items are often irregular, with behaviors like hoarding and salvaging valuable components. The city's CMRF must adapt to manage these emerging categories through specialized facilities and methods.

Factor 6: Outliers (Lamps)

Although lamps contribute minimally to the overall variance, they warrant attention due to persistent improper disposal practices. Given their widespread possession across various consumer segments, this issue remains prevalent, underscoring the need for targeted disposal solutions. The lack of behavioral onus and insufficient recycling infrastructure contribute to these improper disposal practices.

However, it is essential to address the PCA's failure in refining the classification of lamps by grouping them with LEE in Factor 2. This grouping neglects the unique challenges lamps pose, such as hazardous materials (e.g., mercury) and the complexities of recycling. While PCA identifies broad patterns (Jolliffe, 2002), semi-partial correlation coefficients (SPCC) offer a more nuanced analysis by isolating the independent effects of factors such as size, bulk, hazardous components, and recyclability (Cohen et al., 2013). SPCC controls for other variables, providing more precise insights into disposal behaviors. We opted for semi-partial over partial correlation to avoid distorting relationships and enhance data accuracy, thereby improving explanatory power (Kim, 2015).

3.3 Findings from Semi-Partial Correlation Analysis

Exploring Waste Clusters: Statistical Relationships and Insights

The semi-partial correlation coefficients (SPCC) reveal that e-waste categories can be grouped into three distinct clusters (Table 3) based on size, disposal behaviors, infrastructures, policies, and their economic and environmental impacts. This classification aids in developing targeted e-waste management strategies. As Huisman et al. (2019, Part II) suggest, differentiation optimizes collection systems. Precision in processing technologies is also vital for efficiently separating hazardous components from recyclable materials, improving recovery rates, and minimizing environmental impacts.

Table 3. Overview of e-waste clusters

Category	Common (Non-Hazardous)	Common (Hazardous)	Valuable Stocks	Collection System	Recycling System
Cluster 1	Metals, Plastics, Glass, Aluminum, Steel and Iron, Silicon, Rubber, Polyurethane	CFCs, HFCs, Cr6+, HCFCs, Hg, Pb, Cd, PCBs, BFRs, Asbestos, Hg, Pb, Cd, PCBs, BFRs, Cr6+	Au, Ag, Pd, Pt, Cu, Nd, Dy, La, Ce	designated collection points, take-back programs	disassembly, refrigerant recovery, glass and metal recycling
TEE S&M			Au, Ag, Cu, Pd	designated collection points, retail drop-off	disassembly, mercury neutralization, glass and metal recycling
Cluster 2		Hg, Pb, Cd, PCBs, BFRs, Cr6+, Asbestos, As	Au, Ag, Cu, Pd, Rh, Pt, Nd, Dy	take-back programs, dedicated collection points	disassembly, precious metal recovery
SEE			Au, Ag, Pd, Cu, Nd, Dy, Pr, La	designated collection points, take-back programs	disassembly, refrigerant recovery, glass and metal recycling
LEE			Au, Ag, Pd, Cu, Pt, Rh	take-back programs, recycling centers	disassembly, metal and plastic recycling
SICT					
Lamps		Hg, Pb, Cd, PCBs, BFRs	Au, Ag, Pd, Pt	designated collection points, retail drop-off	disassembly, glass and metal recycling

Cluster 1: TEE and S&M

A strong positive correlation (Pearson's $r = 0.509$, $p < 0.001$) exists between TEE (air conditioners, refrigerators, freezers) and S&M (televisions, computer monitors, and other screen-based devices), indicating that consumers often dispose of or recycle these items together. This is mainly due to their similar materials, such as glass, plastic,

copper, and aluminum, which are valuable and highly recyclable. Copper, in particular, has high scrap value, contributing to an efficient recycling process when collected together. However, both categories contain hazardous materials, like refrigerants in TEE and mercury in older CRT televisions, posing environmental and health risks if improperly disposed of (Priya & Hait, 2018). Furthermore, TEE and S&M devices contain precious materials, such as gold and silver, which can be recovered during recycling. In factor analysis, ICT devices were grouped with temperature exchange equipment (TEE) and screens and monitors (S&M) based on shared characteristics. However, correlation analysis reveals a clear distinction, as ICT devices exhibit unique disposal behaviors and recycling complexities. These devices often contain different materials and are more likely to be refurbished or reused, which sets them apart from TEE and S&M in terms of end-of-life management.

Cluster 2: SEE, LEE, and SICT

Within Cluster 2, comprising SEE, LEE, and SICT, moderate to strong positive correlations are observed between these categories. Specifically, the correlation between SEE and LEE is $r = 0.419$ ($p < 0.001$), suggesting that small and large electronic appliances often share similar disposal behaviors. Similarly, the correlation between SEE and SICT is $r = 0.395$ ($p < 0.001$), highlighting a moderate connection in disposal behaviors between small household appliances and small ICT devices. These correlations imply that consumers' disposal habits for these items may be influenced by similar factors, such as material types, available disposal systems, or the convenience of recycling (Kochan et al., 2016; Echegaray & Hannstein, 2017). Consistent with the factor analysis, these devices share common recoverable materials such as glass, plastic, metal, and copper, which can be recycled through disassembly and precious metal recovery processes (Nnorom & Osibanjo, 2008). For example, lithium-ion batteries in small ICT devices are hazardous and require specialized recycling systems to avoid environmental damage. The high reusability of metals like copper, gold, and silver in these devices underscores the importance of improving recycling infrastructure.

Broken Lamps and the Toxic Toll of a Throwaway Society

Disposing of lamps, particularly compact fluorescent lamps (CFLs), presents significant challenges due to hazardous materials like mercury, which require specialized disposal methods (EPA, 2020). The SPCC analysis refined the factor analysis results by highlighting the unique disposal complexities of lighting equipment, distinguishing them from other e-waste categories, and emphasizing the need for separate handling and recycling protocols. The weak correlation between Lamps and other e-waste categories $r = 0.067$ ($p > 0.05$) reflects their unique disposal needs, which consumers often overlook. Without clear disposal guidelines, improper disposal can lead to environmental risks, including mercury contamination. Fluorescent lamps, for instance, contain 3-5 milligrams of mercury per unit and are composed of 90% glass, a material suitable for reuse. Despite achieving 85-90% recycling rates in Europe, global rates remain low due to inadequate infrastructure (Leopoldino et al., 2019).

In the Philippines, the transition from incandescent bulbs to energy-efficient CFLs began in 2010 to reduce energy consumption (GMA News, 2009). However, this initiative overlooked the environmental challenges posed by CFLs' mercury content (USGS, n.d.). With limited recycling infrastructure, improper disposal led to an estimated 25.5 tons of mercury circulating by 2018 (MicroRenewables, 2023), undermining RA 9003's objectives to protect public health and the environment. Modern lamps, including LEDs and CFLs, prioritize convenience over sustainability, discouraging repair and reuse. This, as unclear disposal guidelines and limited repair options, contribute to improper disposal practices. Proposed solutions, such as repurposing lamp glass into geopolymers (Novais et al., 2016), face challenges due to the increasing volume of LEDs (Kumar et al., 2019; Cenci et al., 2020). Improper disposal, particularly in ecosystems like Sarangani Bay, exacerbates environmental risks, as mercury bioaccumulates, posing neurotoxic threats and economic inefficiency by leaving valuable resources unrecycled (Clean Energy Wire, 2021).

Development of a Data-Driven Framework for E-Waste Management

In 2016, General Santos City disposed of an average of 80.12 tons of waste daily, with plastics (51.25%) and paper (28.53%) accounting for the most significant portions (Pareja, n.d.). While e-waste is not explicitly categorized, it is likely included under the "special waste" classification due to its hazardous components, complicating disposal efforts. Researchers, including Ádám et al. (2021) and Ikhlayel (2018), highlight the need to improve municipal solid waste management (MSWM) systems, which often overlap with e-waste recycling processes, as a viable

solution. This is particularly relevant given the frequent mixing of e-waste with general waste in General Santos City (Garcia et al., 2024).

In line with this, the SPCC analysis, summarized in Table 3, provided valuable insights into the relationship between e-waste categories and disposal behaviors, complementing the findings from PCA. Based on these insights, we propose an e-waste management framework that integrates robust institutional mechanisms, positions e-waste as a valuable commodity to formalize urban mining practices and establishes a comprehensive collection system design. The framework also includes the development of advanced processing and recycling infrastructure alongside implementing a structured data management system for effective tracking and reporting.

Institutional Mechanism

The success of sustainable e-waste management in General Santos City hinges on strong policy development, stakeholder engagement, and effective governance. A key strategy is implementing a localized EPR mechanism, which holds manufacturers accountable for their products' entire lifecycle—from design to disposal. EPR encourages the creation of recyclable, reusable, and refurbishable products, reducing e-waste and promoting responsible consumer behavior through clear labeling and disposal instructions (Maitre-Ekern, 2021). Take-back programs, a vital component of EPR, ensure manufacturers are responsible for collecting and recycling products at the end of their lifecycle. These programs incentivize manufacturers to design with recycling in mind. The local government can mandate these take-back systems, ensuring proper collection and processing of discarded electronics. Such systems can be facilitated through partnerships between local government units, manufacturers, and recyclers, with frameworks supported by Republic Acts 9003 and 6969, ensuring comprehensive management of hazardous and e-waste materials.

To address policy gaps, General Santos City can leverage the "governance from below" principle in the Local Government Code of 1991 (Garcia et al., 2024). The city could require manufacturers to establish accessible collection points, including mobile units for remote areas, and provide incentives such as tax breaks for businesses investing in advanced recycling technologies. A robust data collection and monitoring system, driven by an EPR mechanism, is essential for tracking e-waste from collection to recycling. Manufacturers must report sales volumes, collected e-waste, and recycling rates (Khetriwal et al., 2009). Regular audits would ensure compliance with recycling quotas and promote transparency (Osibanjo & Nnorom, 2007). Global initiatives, such as the Waste Electrical and Electronic Equipment (WEEE) Directives, set environmentally sound collection and recycling standards. Circular economy policies promote the recovery of valuable metals and rare earth elements, while collaborative partnerships among governments, private companies, and NGOs drive innovation.

To ensure financial sustainability, service fees can support recycling initiatives. Public-private partnerships (PPP) can enhance infrastructure, expand recycling, and formalize the informal sector, ensuring safer working conditions and greater inclusivity in e-waste management. The Basel Convention advocates for environmentally sound management (ESM) and material recovery through financial mechanisms like collection and pre-processing fees (Basel Convention, n.d.). General Santos City can adopt these practices, using service fees and revenue-sharing models for operational viability. Collection and pre-processing fees generate income, aligning with the convention's financial strategies. Profit-sharing agreements with regional refining facilities could create revenue through urban mining, recovering valuable metals and REEs (Sharma et al., 2021; Xavier et al., 2021; Murthy & Ramakrishna, 2022). Refurbishing components and customizing pre-processing will capture more value before recycling.

Commodification of E-Waste

The recovery of precious metals and rare earth elements (REEs) from e-waste presents a significant economic opportunity, mainly through urban mining. Metals like gold, valued at around \$60 per gram in 2024, and silver, priced at approximately \$0.80 per gram, are highly sought for their conductivity and resistance to corrosion (Kitco, 2024; SilverPrice.org, 2024). Copper, another essential metal used in wiring and circuit boards, is valued at about \$9,000 per metric ton (LME, 2024). These high values underscore the economic potential of extracting valuable metals from e-waste, especially from devices within the various EEE categories highlighted in the literature.

In particular, small ICT devices (e.g., phones, laptops, tablets), screens and monitors (e.g., TVs, computer monitors), temperature exchange units (e.g., refrigerators, air conditioners), and large EEE (e.g., washing machines, large household electronics) are rich sources of valuable metals. Copper is commonly found in these devices' wiring and circuit boards, while precious metals like gold and silver are used in components like connectors, circuit boards, and other critical parts. REEs, such as neodymium, dysprosium, and praseodymium, are essential for producing high-performance magnets in wind turbines, electric vehicles, and smartphones. These REEs are embedded in various e-waste categories, from small ICT devices (for components like hard drives and motors) to screens and monitors (for use in displays and magnets) and even in temperature exchange systems (for use in compressors and cooling systems).

Other valuable elements like europium and yttrium, used in display technologies, and lanthanum and cerium, vital for battery production and catalytic converters, can be found in a broad range of electronic products, including washing machines and refrigerators, as well as in small ICT devices and temperature exchange units. The growing global demand for these REEs, driven by their importance in renewable energy systems and advanced electronics, further emphasizes the need for efficient recovery methods (Shevchenko et al., 2019). Elements such as dysprosium, terbium, neodymium, praseodymium, and europium can fetch between \$500 and \$1,000 per kilogram, depending on market conditions and purity (Mining.com, n.d.), underlining the immense value trapped in these discarded electronic devices.

Implementing advanced e-waste recovery technologies across all categories optimizes the extraction of valuable materials, enhancing resource recovery, reducing landfill waste, and minimizing environmental impact through efficient recycling processes. Combining technological advancements with skills development ensures the safe recovery of these materials while minimizing environmental harm. A comprehensive, integrated approach recovers critical metals and REEs from these diverse categories of e-waste, supporting sustainable practices and generating both environmental and economic benefits (Kara et al., 2022). To address the technological disparity, this study proposes a "Best-of-2-Worlds" approach (Wang et al., 2012). General Santos would manage the initial sorting and separating of e-waste locally while outsourcing complex hazardous waste processing to regional facilities meeting national safety standards (Ikhlayel, 2018). We emphasize ensuring worker safety during sorting and dismantling, underscoring the need for safety protocols, PPE, and training to protect workers.

Collection System Design

The city currently relies on a dual approach, with private waste collectors handling 20% of waste and the informal sector managing 80%, bridging gaps in public infrastructure and ensuring services meet the demands of a growing population (Garcia et al., 2024). The system is under strain, with only three compactors, two dump trucks for the entire city, and three of 26 barangay Material Recovery Facilities (MRFs) non-operational. To improve efficiency, the literature supports our findings, suggesting that grouping the categories into three main clusters enhances organization and management.

Cluster 1, which includes TEE and S&M, relies on designated collection points, take-back programs, and retail drop-off locations for proper disposal. These systems are designed to manage bulky products like air conditioners, refrigerators, televisions, and computer monitors, which are difficult to dispose of due to their size and materials. Retailers and authorized service providers often offer take-back services when consumers replace old items, ensuring proper recycling instead of landfilling. Large appliances can also be dropped off at retail centers, recycling hubs, or unique collection points. Electronics manufacturers and retailers play a crucial role by providing incentives such as discounts or free pickup services to encourage consumers to return old items. For example, a new television purchase might include a discount or pickup service for the old one, ensuring it is properly recycled. Public education campaigns also raise awareness about the dangers of improper disposal and the benefits of recycling valuable metals from old electronics.

In Cluster 2, comprising SEE, LEE, and SICT, the collection system can be enhanced by establishing designated collection points in high-traffic areas, such as shopping centers, electronics stores, and municipal facilities. These locations will provide easy access for consumers to drop off small and large appliances and ICT devices. Furthermore, mobile collection units can be deployed in residential areas to assist with the disposal of larger appliances like washing machines and dishwashers, offering added convenience. Complementing these efforts,

public awareness campaigns are crucial to educating the community on the environmental impacts of improper e-waste disposal and the availability of accessible collection systems.

For Cluster 3, which focuses on Lamps, the collection system should prioritize designated collection points and retail drop-off programs to facilitate proper disposal. Encouraging consumers to return used lamps to designated collection hubs, such as retail locations or dedicated recycling centers, ensures these items are safely handled. Moreover, promoting the adoption of LED technology, which is safer and has a longer lifespan compared to traditional mercury-containing lamps, will reduce the volume of hazardous waste. Focusing on non-hazardous alternatives in lamp design will also help mitigate long-term environmental and health risks associated with mercury.

Processing and Recycling Systems

The recovery and recycling component highlights the critical role of General Santos City's CMRF in advancing recycling and refurbishment efforts. Equipped with machinery to process plastics, metals, and glass, the facility supports the city's environmental goals of reducing waste and conserving resources by reprocessing materials into new products (Mmereki et al., 2016). In 2021, the city proposed securing nearly ₱2 billion in funding from the Land Bank of the Philippines (LBP) to enhance its solid waste management program. This loan would finance improvements such as acquiring heavy equipment, constructing a hospital waste facility, and developing a weighbridge (BIMP-EAGA, 2018). These investments will optimize waste management, recycling processes, and handling hazardous materials like medical and e-waste. The city is also expanding its infrastructure with a biohazardous waste treatment facility to meet regulatory standards and work toward DENR accreditation under Republic Act 9003 (Garcia et al., 2024). Also under consideration is adopting a Waste-to-Energy (WTE) model, which would convert waste into usable energy, aligning with the city's renewable energy goals (BIMP-EAGA, 2018). In conjunction with this, we recommend collaborating with businesses specializing in refurbishing used electronics, as this could generate economic opportunities while promoting environmental sustainability.

The reusability of items under the TEE and S&M categories (Cluster 1) is often limited due to hazardous materials. For example, refrigerants in air conditioners and refrigerators pose significant environmental risks if not adequately recovered. Similarly, mercury in light bulbs or screens complicates the reuse of specific components. Despite these challenges, the metals and plastics in these devices offer considerable reusability potential. Programs focusing on recovering these materials can significantly reduce environmental impact. The recycling system for these items typically involves disassembly, refrigerant recovery, and metal recycling. Disassembly separates materials, ensuring hazardous substances like mercury or refrigerants are safely removed and neutralized before the remaining parts are processed for recycling. Metals like copper and aluminum can be recovered through traditional methods, while specialized recovery systems are necessary for hazardous components like mercury and refrigerants.

Several alternatives and actions can be integrated. Introducing refrigerant recovery systems can ensure the safe extraction and neutralization of harmful substances prior to recycling. Additionally, incentivizing eco-friendly refrigerants, such as HFOs, which have a lower environmental impact, can significantly mitigate the harmful effects of refrigerants in air conditioners and refrigerators. Promoting the design and use of eco-friendly products that are easier to disassemble and contain fewer hazardous materials will streamline the recycling process and make it safer (Widmer et al., 2005). Additionally, mercury-neutralization technology for screens and monitors is a critical development that can reduce the environmental risks associated with electronic waste. Local recycling hubs can be established to streamline the collection and processing of these items. These hubs can focus on both non-hazardous materials (glass, plastic, metal) and hazardous materials (refrigerants, mercury), ensuring that waste is processed in an environmentally friendly manner.

For Cluster 2 (SEE, LEE, and SICT), a multifaceted recovery and recycling system is necessary to handle both non-hazardous and hazardous materials while prioritizing environmental safety. The system begins with disassembly and sorting at designated recycling centers, allowing for the separation of materials like metals, plastics, glass, and copper. Devices containing hazardous materials, such as lithium-ion batteries in small ICT devices and refrigerants in large EEE items like refrigerators and air conditioners, require specialized recovery systems.

Lithium-ion batteries should be processed using battery recovery systems to safely extract and neutralize harmful chemicals, while refrigerant recovery systems should be in place to capture and dispose of gases from appliances.

Material-specific recycling is crucial in this process. Metals like copper, aluminum, and gold can be recovered through advanced mechanical processes or smelting, enabling their reuse in manufacturing new products. Glass and plastics, commonly found in screens and small and large device casings, should be processed through dedicated recycling plants to convert these materials into new products. Additionally, precious metal recovery techniques can extract valuable materials like gold, silver, and copper from small ICT devices, such as smartphones and laptops, reducing the environmental impact of mining.

The recovery and recycling system for Lamps (Cluster 3) primarily involves disassembly, which allows for the separation of glass, plastic, and aluminum components—highly recyclable materials that can be reused in the production of new products. The glass and metal parts can be processed through glass recycling plants and metal recycling facilities to ensure efficient reuse. However, the key challenge with lamps is the mercury content, which requires specialized handling. A safe disposal program for mercury-containing lamps should be implemented, utilizing mercury neutralization techniques to remove and safely contain the hazardous substance.

Logistical and material supply contracts could generate income by optimizing e-waste transportation and securing competitive pricing for recovered materials through urban mining. Partnerships with eco-friendly processing facilities can earn carbon credits, generating revenue. Corporate social responsibility (CSR) initiatives with multinational companies could fund green projects, enhancing sustainability. Focusing on skill development and job creation in dismantling, sorting, and extraction processes offers socioeconomic benefits, empowering local citizens and keeping operational costs manageable while furthering environmental goals. Promoting General Santos City as a leader in sustainable waste management, mainly through urban mining, could attract global recognition, funding, and further partnerships, reinforcing its position as an innovator.

Data Collection and Monitoring

Effective data collection and monitoring for e-waste management in General Santos City should combine localized strategies with advanced technologies. Barangay-based MRFs can serve as key collection hubs, enhanced by Internet-of-Things (IoT)-enabled smart bins that provide real-time data on e-waste volumes and types (Khan & Ahmad, 2022). This innovative technology enables tracking and sorting, improving recycling efficiency. Integrating this data into a centralized platform will offer valuable insights for better decision-making and resource recovery. Additionally, to strengthen the EPR framework, producers and distributors should report their electronic product sales and recycling contributions, ensuring alignment with local e-waste management goals.

Community engagement plays a crucial role in e-waste management, with digital tools such as mobile apps enabling households and businesses to log e-waste disposals, access collection schedules, and request pickups. Manual sorting at MRFs must be closely monitored through detailed logging systems, supported by periodic audits to ensure the safe handling and efficient categorization of e-waste. Worker safety can be prioritized by implementing regular safety checks and providing protective equipment. Additionally, the Central MRF should document key metrics on recycling, refurbishment, and resource recovery to evaluate operational effectiveness. WTE facilities should use real-time monitoring to measure energy outputs and conversion efficiency for non-recyclable waste, ensuring optimal performance. Public awareness campaigns should be data-driven, using surveys and feedback to assess their reach and impact. All collected data should be consolidated into comprehensive reports, providing decision-makers with insights to identify areas for improvement, optimize resource allocation, and ensure the sustainability of the system.

4.0 Conclusion

This study leverages the integration of Principal Component Analysis (PCA) and Semi-Partial Correlation Coefficients (SPCC) to explore the intricate dynamics of e-waste management. PCA effectively reduces large datasets, such as survey responses or environmental metrics, into principal components that capture the most significant variance. This process highlights key patterns, such as dominant disposal behaviors and material flows. SPCC enhances PCA by isolating the unique contributions of individual variables—such as socioeconomic factors or policy interventions—on e-waste generation and recycling rates while controlling for confounding variables.

This complementary approach ensures that the study uncovers broad trends and specific relationships, providing a multidimensional perspective on e-waste dynamics that can guide the development of targeted, sustainable management practices.

The methodology contributes a synergistic analytical framework that significantly advances the field of sustainable e-waste management. Strengthening the theoretical foundation of e-waste studies offers practical utility for crafting evidence-based, scalable solutions. Future research should address sample size and scalability limitations to refine and validate this framework. Expanding the sample size across diverse demographics and regions will increase the reliability of findings, capturing finer variations in e-waste behaviors and policy impacts. Larger datasets will also enhance the effectiveness of PCA and SPCC, leading to a more comprehensive understanding of system dynamics. Scalability is essential to adapt the framework across various operational levels, from local to national, and conducting comparative regional analyses will ensure its global applicability in addressing e-waste challenges. Future studies should expand to other Philippine cities to validate the framework's scalability.

This study delivers actionable, evidence-based strategies for localized e-waste management. The proposed framework, built on five interconnected pillars – Collection System Design, Processing and Recycling Systems, Data Collection and Monitoring, Formalization of Urban Mining, and Enhanced Institutional Mechanisms – offers a comprehensive approach to addressing e-waste challenges. Each pillar is vital in closing gaps in e-waste management and ensuring efficient collection, recycling, and resource recovery. Addressing policy gaps, the framework advocates for a stepwise strategy that begins with establishing a strong policy foundation, correcting regulatory deficiencies, and considering political dynamics. It then progresses towards gradually adopting advanced technologies and processes to ensure scalable and adaptable systems for effective e-waste handling.

Based on the findings, the improper disposal of broken lamps, particularly those containing hazardous materials like mercury, emerges as a critical urban concern. Density distribution analysis reveals that many consumers are unaware of the hazardous components in lamps, leading to improper disposal and significant environmental risks, such as mercury contamination. PCA and SPCC highlight weak correlations between lamps and other e-waste categories, suggesting that lamps should be treated separately and require specialized disposal strategies. The urgent need to address the *ad hoc* disposal of lamps in homes, establishments, and institutions offers a feasible solution for local governments, considering existing policy gaps, technological limitations, and infrastructure constraints. Governments can introduce targeted policies, such as clear disposal guidelines and mandatory recycling processes, to ensure proper lamp disposal. Technological solutions, such as mercury recovery and specialized recycling facilities, are already available, making the issue solvable with accessible technology. From an infrastructure standpoint, setting up dedicated collection points in high-traffic areas presents a practical solution that would not require significant changes to current solid waste management systems. In contrast, other e-waste categories, such as large appliances and smaller electronics, necessitate more complex infrastructure and technological interventions. Thus, addressing the disposal of broken lamps offers a manageable and immediate solution to mitigate environmental risks, aligning with available resources and capabilities.

5.0 Contributions of Authors

Garcia R.M. was responsible for the study's conceptualization, methodology, data collection, and data analysis. He also handled data visualization, authored the original draft, and contributed to the final revision of the manuscript.

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7.0 Conflict of Interests

The author declares no conflict of interest, confirming that no personal, financial, or professional relationships influenced the research outcomes. The work was conducted with the sole intention of advancing academic knowledge, and no external factors impacted the objectivity or integrity of the study.

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