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Design and Development of an e-Waste Management System

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Abstract
The rapid proliferation of electronic devices has led to a significant global challenge: the management of electronic waste (e-waste). The improper disposal of e-waste, containing hazardous substances such as heavy metals and toxic chemicals, has dire consequences for environmental sustainability and human health. Despite advancements in e-waste management in developed nations, many regions, including Zambia, face considerable barriers to implementing efficient and sustainable systems (Baldé *et al*., 2017; Forti *et al*., 2020). This research focuses on designing and developing an integrated e-waste management system that harnesses technological innovation, regulatory collaboration, and stakeholder engagement to address these challenges.

This study presents a computer-based application designed to streamline the lifecycle management of e-waste, encompassing collection, transportation, recycling, and final disposal. The application introduces automated calculation of disposal fees based on parameters such as waste volume and distance to disposal sites, enhancing transparency and efficiency. The system development was informed by surveys and questionnaires distributed among key stakeholders, including the Zambia Environment Management Agency (ZEMA), the Ministry of Health, the Ministry of Technology and Sciences, and the public.

The research identified critical gaps in existing e-waste management systems, such as limited public awareness, inefficient collection mechanisms, and inadequate regulatory enforcement. Drawing from global best practices, such as life cycle assessment (LCA), material flow analysis (MFA), multi-criteria analysis (MCA), and extended producer responsibility (EPR), the proposed system integrates these tools into a cohesive framework tailored to Zambia's socio-economic context (Kiddee *et al*., 2013; Singh *et al*., 2021).

The proposed e-waste management system demonstrates the potential to mitigate environmental and health risks associated with improper e-waste disposal. By fostering public engagement and adopting eco-design principles, the system promotes sustainable resource recovery, environmentally responsible disposal, and effective recycling practices. The findings emphasize that the combined application of regulatory frameworks, technological innovation, and stakeholder input significantly enhances the system's effectiveness.

This research underscores the importance of an integrated, multi-stakeholder approach to e-waste management. The proposed system not only addresses existing inefficiencies but also aligns with global sustainability goals. Its implementation could serve as a model for other regions facing similar challenges, contributing to broader efforts in environmental conservation and sustainable development.

Keywords: Applications, Public Platforms, Recycling, Disposal, Management, System, e-Waste, Sustainability

1. Introduction
1.1 Background
Electronic waste, commonly referred to as e-waste, poses a significant environmental and health threat, with global generation estimated at approximately 50 million tons annually—a figure projected to rise as technology usage expands worldwide (Global E-waste Statistics Partnership, 2020). E-waste encompasses a variety of discarded electronic devices, including mobile phones, computers, and batteries, which often contain hazardous materials such as lead, mercury, cadmium, and brominated flame retardants. The improper disposal of these materials can result in the leaching of toxic substances into soil and waterways, leading to widespread pollution and posing serious risks to both human health and ecological systems (Forti *et al*., 2020).

In regions such as Zambia, the lack of adequate e-waste disposal infrastructure frequently leads to practices such as direct dumping into landfills, rivers, and drainage systems. This situation is exacerbated by insufficient policy enforcement and ineffective manual handling methods that contribute to environmental degradation. Although regulatory bodies like the Zambia Environmental Management Agency (ZEMA) have established guidelines for e-waste management, these regulations are often overlooked in practice, allowing hazardous waste to accumulate without appropriate safeguards (ZEMA, 2023) [30].

To combat this escalating issue, innovative technologies are being implemented to enhance e-waste management practices. Geographic Information Systems (GIS), artificial intelligence (AI), and Internet of Things (IoT) solutions are increasingly being utilized to track e-waste and facilitate its safe disposal. For example, digital platforms can connect consumers with certified recycling facilities, offer incentives for responsible disposal practices, and monitor illegal dumping activities. The modernization of waste management through these technological applications enables authorities to engage effectively with the public while reducing environmental impacts and enhancing public health and safety (UNEP, 2023) [13].

These technological advancements present a sustainable approach to e-waste management that relies on robust collaboration between government entities and local communities. By integrating these solutions into broader waste management frameworks, it is possible to minimize the harmful effects of e-waste and promote a healthier environment for future generations (Kiddee *et al*., 2013). The integration of innovative technologies not only addresses the immediate challenges posed by e-waste but also fosters long-term sustainability through improved resource recovery practices.

1.2 Background of the Research

The term electronic waste (e-waste) refers to discarded electrical and electronic equipment that is no longer usable due to obsolescence, malfunction, or the lack of repair parts. This category of waste has emerged as one of the fastest-growing waste streams globally, with an estimated 50 million tons generated annually, significantly impacting the environment and public health (Baldé *et al*., 2017; Forti *et al*., 2020). The improper disposal of e-waste poses substantial risks as it releases hazardous substances such as mercury, lead, cadmium, polychlorinated biphenyls (PCBs), benzene, and dioxins into the environment. These toxic materials can contaminate soil and water resources, leading to severe health issues and ecological damage.

The rapid advancement of technology and increasing consumer demand for new electronic devices contribute to the surge in e-waste production. Many electronic items contain valuable materials that can be recovered; however, improper disposal methods often lead to environmental degradation rather than resource recovery (Kiddee *et al*., 2013). The Basel Convention classifies e-waste into hazardous or non-hazardous categories based on the presence of toxic materials. E-waste containing harmful substances is categorized as hazardous waste, while other components may include precious metals like gold and copper that can be recycled (Basel Convention, n.d.) [6].

Effective management strategies are essential to mitigate the environmental impacts of e-waste and promote sustainable resource recovery practices. The challenges associated with e-waste management are particularly pronounced in developing countries, where limited infrastructure, economic constraints, and a lack of awareness hinder effective disposal and recycling efforts (Reecollabb). These nations often rely on informal recycling sectors that pose significant health risks due to inadequate safety measures and exposure to toxic substances.

Recent advancements in technology have paved the way for innovative solutions in e-waste management. Developing web-based systems utilizing the Internet of Things (IoT) and machine learning algorithms provides a promising avenue for enhancing e-waste collection, monitoring, and recycling processes. These systems can facilitate real-time tracking of e-waste levels in collection bins, optimize collection schedules, and improve stakeholder engagement by providing up-to-date information on e-waste management activities (Kang *et al*.; Farjana *et al*.).

In conclusion, addressing the growing challenge of e-waste requires a comprehensive approach that combines technological innovation with robust regulatory frameworks and public awareness initiatives. By leveraging modern technologies in the design and development of a web-based electronic waste management system, it is possible to create a more efficient, sustainable solution that protects human health and promotes environmental sustainability.

1.3 Problem Statement

Electronic waste, or e-waste, poses a serious environmental and public health hazard. Each year, an estimated 50 million tons of e-waste is generated worldwide, a figure projected to grow rapidly as technology advances and the global consumption of electronic devices increases. This waste includes discarded phones, computers, batteries, televisions, and other digital devices that contain hazardous materials such as lead, mercury, cadmium, and brominated flame retardants. When improperly disposed of, these toxic substances leach into soil and waterways, causing pollution that can harm plants, animals, and human health.

In many areas, including Zambia, the improper disposal of e-waste often leads to direct dumping into landfills, rivers, seas, oceans, and drainage systems, exacerbating environmental damage. The lack of an efficient, safe disposal infrastructure or policy enforcement worsens the situation. Current manual e-waste management methods have proven largely ineffective due to their reliance on unregulated practices and insufficient public awareness of the associated dangers. Despite guidelines set by environmental regulatory bodies like the Zambia Environmental Management Agency (ZEMA), e-waste is often disposed of unsafely, ignoring ecological protection procedures.

1.4 Objective

1.4.1 General Objective

The project aims to develop a modern e-waste management system using advanced technology to address the environmental and health risks associated with electronic waste disposal.

1.4.2 Specific Objectives

- Design and development of a web/application-based electronic waste management system.
- Design and development of the e-waste management

system which will allow the client to bargain the price of their e-waste.
- Design and development of the system which will allow the client to upload pictures of the e-waste which they want to dispose of.

1.5 Research Questions
- How can a web or application-based electronic waste management system be effectively designed and developed to streamline e-waste management processes?
- What mechanisms can be incorporated into an e-waste management system to enable clients to negotiate the price of their e-waste?
- What design features are required for a system that allows clients to upload images of the e-waste they want to dispose of for efficient processing and valuation?

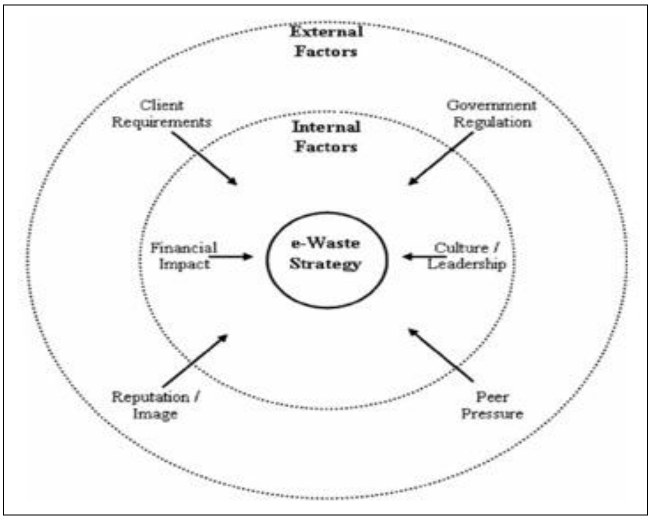
1.6 Conceptual Framework
A conceptual framework is a crucial tool in system design, used to define the context, scope, and fundamental structure of a modelled system. It acts as a blueprint, mapping out the system's core elements, and illustrating how they interact both internally and with external entities. By visually representing these relationships, the framework clarifies the system's operational context and the scope of its functionality, which is essential for stakeholders and developers to understand the full breadth of the system's interactions and boundaries.

In this framework, a high-level overview is presented, often as a Context-Level Data Flow Diagram (DFD) or a Level 0 DFD. This diagram depicts the entire system as a singular, high-level process that interacts with external entities, such as users, other systems, and external databases, providing a macro perspective of data flow. It enables stakeholders to grasp the system's primary inputs and outputs, how external entities influence the system, and how the system impacts those entities in turn (Nifty *et al.*, 2015). The clear visualization of these interactions is foundational in identifying both the limitations and capabilities of the system early in the design phase, minimizing potential errors and misalignments as the project progresses.

One of the key roles of the context diagram in the conceptual framework is to establish well-defined system boundaries. These boundaries distinguish what is inside the system (under its control and operation) from what lies outside of it. By delineating this scope, the context diagram helps prevent "scope creep," where unplanned functions and interactions can overextend the project. Additionally, setting these boundaries allows development teams to focus resources on essential features, avoiding unnecessary complexity and ensuring all critical data flows are accurately captured (Degif *et al.*, 2017).

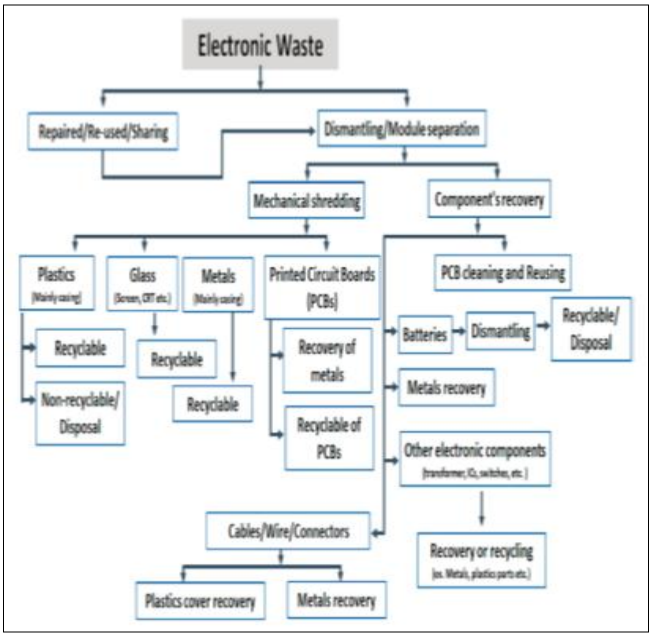
In terms of data design, the context diagram serves as an initial, yet essential, step that informs subsequent design phases. By creating a simplified, high-level model of the system's data exchanges, developers can outline preliminary requirements for data storage, processing, and security. This framework also plays a critical role in communication between technical and non-technical stakeholders by providing a straightforward illustration of complex processes, making it easier to reach a shared understanding of system functionality and expectations.

The conceptual framework, thus, is more than just a static diagram. It is a dynamic tool that sets the stage for detailed system modelling, defining the structural and operational blueprint that will guide the entire development lifecycle. Its influence extends beyond system modelling, impacting the approach to requirements gathering, system testing, and validation, and ultimately aligning the final system with its intended purpose and user needs.



Source: Research Gate

Fig 1: Conceptual model of e-waste strategy determinants



Source: Research Gate

Fig 2: Schematic diagram of the generic e-waste management model

2. Literature Review
The rapid proliferation of electronic devices has created a significant global challenge: managing electronic waste (e-waste). As the demand for electronics increases, so does the volume of e-waste, which contains hazardous substances such as heavy metals and toxic chemicals. The improper disposal of e-waste can have dire consequences for environmental sustainability and human health, particularly in developing regions like Zambia. Despite advancements in e-waste management in developed nations, Zambia faces

considerable barriers, including inadequate infrastructure, limited public awareness, and insufficient regulatory enforcement (Baldé *et al*., 2017; Forti *et al*., 2020).

E-Waste Management Challenges in Zambia

Zambia's e-waste management landscape is characterized by several challenges. A report by the Zambia Environmental Management Agency (ZEMA) highlights that the country lacks facilities to manage e-waste in an environmentally sound manner. Most e-waste is disposed of in dumpsites, with approximately 90% of the population unaware of the risks associated with careless disposal (ZICTA, 2018) [37] 13. The increasing volume of e-waste is exacerbated by the influx of second-hand equipment from developed countries, which often consists of outdated devices nearing the end of their life cycle (ZICTA, 2019) [26] 13.

Research indicates that significant barriers to effective e-waste management in Zambia include a lack of funding for recycling technologies and inefficient infrastructure (Sanana & Mwanza, 2024) [36] 2. Furthermore, existing regulatory frameworks are not adequately enforced, leading to a situation where e-waste is often openly burned or improperly disposed of, releasing toxic chemicals into the environment (Msimuko, 2020) [38] 14.

Proposed Integrated E-Waste Management System

In response to these challenges, this research focuses on designing and developing an integrated web-based electronic waste management system tailored to Zambia's socio-economic context. This system aims to streamline the lifecycle management of e-waste through enhanced collection, transportation, recycling, and final disposal processes. The proposed application introduces automated calculations for disposal fees based on parameters such as waste volume and distance to disposal sites, thereby enhancing transparency and efficiency.

The development of this system was informed by surveys and questionnaires distributed among key stakeholders, including ZEMA, the Ministry of Health, and the Ministry of Technology and Sciences. The research identified critical gaps in existing systems: limited public awareness regarding e-waste hazards, inefficient collection mechanisms, and inadequate regulatory enforcement (Sanana & Mwanza, 2024) [36] 2.

Global Best Practices in E-Waste Management

To inform the design of this integrated system, global best practices were examined. Techniques such as life cycle assessment (LCA), material flow analysis (MFA), multi-criteria analysis (MCA), and extended producer responsibility (EPR) were integrated into a cohesive framework aimed at addressing Zambia's unique challenges (Kiddee *et al*., 2013; Singh *et al*., 2021) 2. For instance:

- Life Cycle Assessment (LCA) helps evaluate environmental impacts associated with all stages of a product's life.
- Material Flow Analysis (MFA) provides insights into the flow of materials through the economy.
- Multi-criteria analysis (MCA) assists in evaluating different options based on multiple criteria.
- Extended Producer Responsibility (EPR) encourages manufacturers to take responsibility for their products throughout their lifecycle.

Impact on Environmental Sustainability and Public Health

The proposed e-waste management system has the potential to significantly mitigate environmental and health risks associated with improper e-waste disposal. By fostering public engagement and adopting eco-design principles, it promotes sustainable resource recovery and environmentally responsible disposal practices. The findings emphasize that combining regulatory frameworks with technological innovation and stakeholder input can enhance system effectiveness.

This research underscores the importance of an integrated approach involving multiple stakeholders in e-waste management. By addressing existing inefficiencies and aligning with global sustainability goals, the proposed system could serve as a model for other regions facing similar challenges. Its implementation may contribute to broader efforts in environmental conservation and sustainable development.

As Zambia grapples with increasing volumes of e-waste amidst rising technological consumption, developing an effective management system is imperative. This research not only identifies critical gaps but also proposes actionable solutions that leverage technology and stakeholder collaboration to foster a sustainable future for electronic waste management in Zambia.

Thematic Area Developed from Objective One

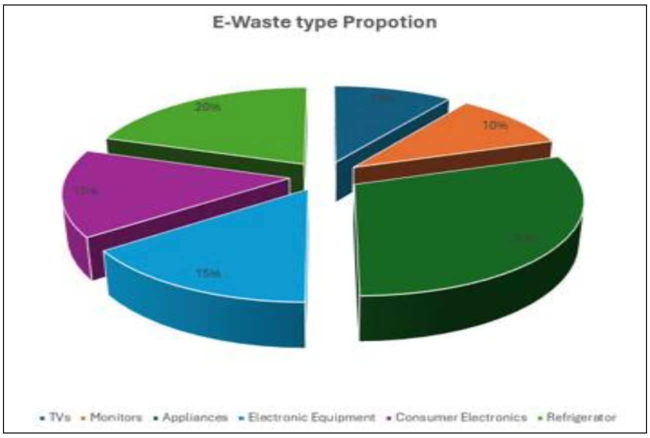
This study draws on scholarly articles that illuminate the complexities of managing e-waste in developing nations, particularly in Zambia. The rapid proliferation of mobile phones equipped with advanced functionalities has significantly contributed to the increasing volume of electronic waste. Researchers and policymakers are increasingly alarmed by the escalating amounts of e-waste, as it poses severe environmental and health risks (Baldé *et al*., 2017; Forti *et al*., 2020). The lack of effective management strategies in these regions exacerbates the situation, leading to improper disposal methods that further threaten public health and environmental integrity (Kiddee *et al*., 2013).

Thematic Area Developed from Objective Two

In Zambia, the management of electronic waste is predominantly manual, lacking an efficient electronic disposal system. The process often requires individuals to contact the Zambia Environmental Management Agency (ZEMA) for guidance, which can be time-consuming and inefficient. Consequently, many individuals abandon their e-waste rather than navigate this cumbersome process (ZEMA, 2023) [30]. This inefficiency highlights the urgent need for a streamlined e-waste management system that can facilitate proper disposal and recycling practices.

Considerations on Waste Management

According to the Southern African Development Community (SADC) Regional Statistics Project P175731 – Electronic Waste Management Plan (March 2023), the term "electronic waste" encompasses all types of electrical and electronic equipment (EEE) that have been discarded, are irreparable, or have reached the end of their life cycle. E-waste includes a wide range of items such as laptops, desktops, tablets, televisions, mobile phones, and household appliances. While e-waste is a general term, it poses significant risks due to the hazardous materials it contains, which can adversely affect human health and environmental quality if not managed properly (SADC, 2023) [18].



Source: Mario and Casy 2018

Fig 3: Schwarzer *et al.* 2015: The E-waste type proportion

Thematic Area Developed from Objective Three

The labour-intensive nature of e-waste management often leads to improper treatment and disposal methods, resulting in significant environmental and public health hazards. Traditional waste management processes are frequently lengthy and complex, causing many discarded electronics to be burned or buried without adequate treatment (Schwarzer *et al*., 2015). Burning e-waste releases harmful pollutants such as dioxins and furans into the atmosphere, which pose severe health risks to nearby communities by increasing the likelihood of respiratory illnesses, cancer, and other chronic conditions (Mario & Casy, 2018) [17].

Conversely, burying e-waste without proper containment allows hazardous substances to leach into soil and groundwater systems over time. This leaching disrupts ecosystems by killing essential microorganisms and plants while also contaminating drinking water supplies and agricultural land (Step Initiative, 2016). As a result, bioaccumulation occurs in food crops and livestock, posing direct risks to human health.

The adverse effects of improper e-waste management extend beyond local environments; they contribute to global environmental degradation. As electronic devices become increasingly ubiquitous, e-waste accumulation has reached alarming levels worldwide. Developing countries often bear the brunt of this issue as they receive toxic e-waste from around the globe without adequate infrastructure for safe disposal (UNEP, 2020) [9].

Addressing these challenges necessitates a coordinated approach involving regulatory frameworks, technological innovations, and public awareness campaigns. Implementing an effective e-waste management system such as a digital application connecting users with certified disposal providers can alleviate inefficiencies in waste processing. This approach ensures environmentally safe handling of e-waste while promoting responsible recycling practices.

Ultimately, transforming e-waste management is crucial for reducing harmful pollutants released into the environment and safeguarding communities from health risks associated with toxic exposure. By adopting responsible e-waste management practices, we can work towards a cleaner, safer, and more sustainable future.

2.1 Related works

The growing concern over electronic waste (e-waste) has prompted extensive research into effective management systems aimed at mitigating its environmental and health impacts. This article reviews various studies that focus on the design and development of e-waste management systems, highlighting innovative approaches and methodologies employed by researchers across different contexts.

Product-Service Systems for E-Waste Management

Ndunda (2018) [23] conducted a comprehensive study on the e-waste management practices at the Waste Electrical and Electronic Equipment Centre in Nairobi County, Kenya. This research explored existing e-waste management systems and compared them with practices in Switzerland and India, both recognized for their advanced e-waste handling methodologies. Ndunda's study identified significant gaps in collection, transportation, financing, consumer awareness, and stakeholder collaboration in Kenya's e-waste management framework. The research utilized a mixed-methods approach, employing surveys and qualitative analysis to develop a product-service system that shifts the focus from merely providing products to offering integrated systems of products and services. This approach emphasizes collaboration among stakeholders to enhance e-waste management efficiency (Ndunda, 2018) [23].

Smart E-Waste Management Systems

A study by Al Duhayyim *et al*. (2023) [19] proposed a smart e-waste management system leveraging the Internet of Things (IoT) and deep learning techniques for object detection. This system aims to support green city initiatives by facilitating better e-waste management practices. The researchers developed an innovative technique called AEOIDLSWM, which combines artificial ecosystem-based optimization with deep learning models to classify waste types using IoT-based camera sensors. This approach not only improves waste classification accuracy but also enhances sustainability efforts by ensuring efficient waste management practices in urban settings (Al Duhayyim *et al*., 2023) [19].

Mobile Applications for E-Waste Disposal

Another significant contribution comes from a study that designed a mobile application called E-Waste System (EWS), which serves as a platform for public engagement in e-waste disposal. The application features geolocation capabilities to help users locate nearby e-waste collection points, thereby encouraging responsible disposal practices. Users can earn points based on the type of e-waste they recycle, fostering community involvement in sustainable waste management (Academic Inspired, 2023) [20]. This model underscores the importance of technology in raising awareness and facilitating proper e-waste handling among the public.

IoT-Based E-Waste Collection Systems

Kang *et al*. (2023) developed an intelligent collection system specifically for Malaysia's e-waste recycling sector. Their design incorporates ultrasonic sensors within smart collection boxes that monitor e-waste levels and communicate with a cloud-based database to schedule pickups when thresholds are reached. This system not only enhances operational efficiency but also provides users with a mobile application for the convenient disposal of household e-waste (Kang *et al*., 2023). Such innovations highlight the role of IoT in streamlining e-waste collection processes.

Machine Learning Applications in E-Waste Management

Farjana *et al*. (2023) [21] explored the integration of machine learning techniques into e-waste management through an IoT-based system that utilizes ultrasonic sensors for real-time monitoring of e-waste levels. Their research emphasizes the use of Generative Adversarial Networks (GANs) for distinguishing different types of e-waste, thereby improving recycling processes significantly. By incorporating cloud-based data analysis, this system aims to optimize waste collection schedules based on predictive analytics (Farjana *et al*., 2023) [21].

The body of research surrounding the design and development of electronic waste management systems reveals a trend toward integrating technology, particularly IoT, machine learning, and mobile applications to enhance efficiency and sustainability in e-waste handling. These studies collectively highlight the necessity for innovative solutions tailored to local contexts while promoting public awareness and stakeholder collaboration.

As electronic devices continue to proliferate globally, effective management systems will be crucial in addressing the challenges posed by e-waste. Future research should focus on refining these technologies and exploring their applicability across diverse socio-economic landscapes to ensure comprehensive solutions for sustainable e-waste management.

2.2 Case Study

During the literature review, the Zambia Railways Telecommunications radio workshop in Kabwe was visited. It was reviewed that a huge amount of e-waste is pending proper disposal (Ref. Fig 4). By demonstrating how the application works, ZRL is trying to partner with the E-TECH RECYCLING LIMITED Company of Lusaka to find the best way of disposing of its e-waste.

Fig 4: Self: The following images depict Zambia Railways Limited's E-waste status at the Kabwe Radio Workshop:

2.3 Gaps in the Literature Review

The literature review on the design and development of an e-waste management system in Zambia highlights several critical issues, yet it also presents notable gaps that could be addressed to enhance the research's depth and applicability. Below are identified gaps categorized by thematic areas:

Lack of Local Case Studies

The review primarily discusses challenges and proposed solutions without referencing specific local case studies that demonstrate successful e-waste management practices within Zambia or comparable developing countries. Incorporating such examples could provide practical insights and validate the proposed solutions, showcasing what has worked in similar contexts.

Insufficient Stakeholder Analysis

While key stakeholders such as ZEMA and the Ministry of Health are mentioned, the review lacks a detailed analysis of their roles, responsibilities, and interactions within the e-waste management framework. A thorough stakeholder analysis could identify potential conflicts, synergies, and opportunities for collaboration that are essential for effective implementation (Sanana & Mwanza, 2024) [36] 2.

Assessment of Cultural Factors

The literature does not address cultural attitudes towards waste disposal and technology usage in Zambia. Understanding local perceptions and behaviours regarding e-waste is crucial for designing effective public awareness campaigns and educational programs aimed at improving disposal practices (Baldé *et al*., 2017) 1.

Economic Implications

The economic implications of proposed e-waste management strategies are not sufficiently explored. An evaluation of the cost-benefit analyses related to recycling technologies and infrastructure investments could strengthen arguments for funding and policy support, providing a clearer picture of economic viability (Msimuko, 2020) [38] 1.

Regulatory Framework Evaluation

Although the review mentions inadequate regulatory enforcement, it does not critically evaluate existing legal frameworks governing e-waste management in Zambia. A comprehensive review of current laws, their effectiveness, and existing gaps would provide a clearer understanding of necessary regulatory changes (ZICTA, 2018) [37] 1.

Technological Innovations

The focus on a web-based system is prominent; however, the review does not discuss other technological innovations that could complement this system. Exploring mobile applications for public engagement or IoT solutions for tracking e-waste could enhance the overall effectiveness of the proposed management system (Kiddee *et al*., 2013) 2.

Long-Term Sustainability Measures

While immediate solutions to current challenges are emphasized, there is insufficient discussion on long-term sustainability measures that should be integrated into e-waste management strategies. This includes considerations for future technological advancements and changing consumer behaviours (Singh *et al*., 2021) 2.

Monitoring and Evaluation Framework

The conclusion mentions ongoing monitoring but lacks a detailed framework for evaluating the effectiveness of the proposed e-waste management system post-implementation. Establishing clear metrics for success would be essential for assessing impact over time (Sanana & Mwanza, 2024) [36] 2.

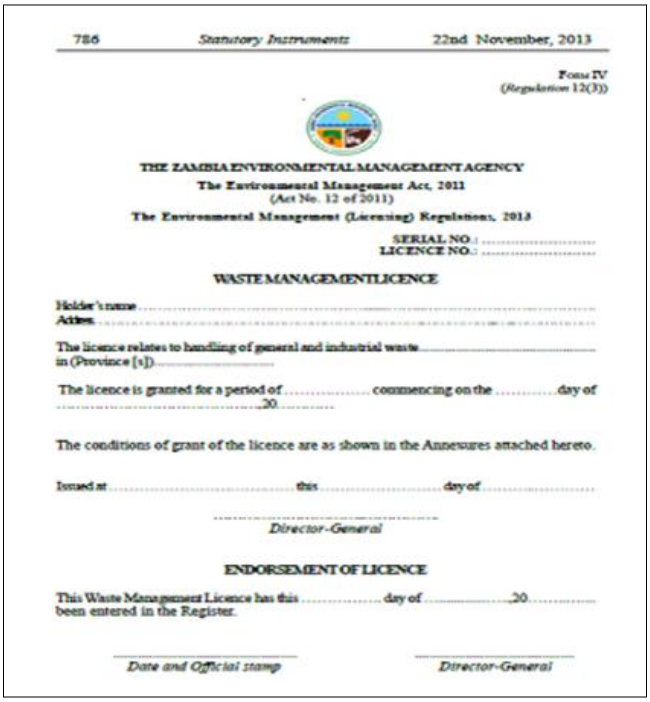
Public Engagement Strategies

The identification of public awareness as a gap is noted; however, specific strategies to effectively engage communities in e-waste management efforts are not proposed. Tailored communication strategies that resonate with local populations would be crucial for fostering participation (ZICTA, 2019) [26] 1.

By addressing these gaps, the research could provide a more robust framework for understanding and improving e-waste management in Zambia, ultimately contributing to better environmental sustainability and public health outcomes.

Zambian Law on E-Waste Management

The Environmental Management (Licensing) Regulations (SI. No 112 of 2013) implemented the Environmental Management Act 2011 which concerns a wide variety of matters regarding environmental protection, including air quality control, waste management, hazardous waste, and other substances harmful to the environment such as pesticides and ozone-depleting substances. E-waste belongs to the fifth schedule, regulation 18 (1), list of hazardous wastes, 'Waste electronic or electronic assemblies….' Any contractor contracted to treat, handle, transport, store, dispose of, or trade-in such waste must hold a ZEMA hazardous waste license. Reference is drawn to the Fig 5 showing a sample of the ZEMA waste management Licence.


786 Statutory Instruments 22nd November, 2013

Form IV
(Regulation 12(3))

THE ZAMBIA ENVIRONMENTAL MANAGEMENT AGENCY
The Environmental Management Act, 2011
(Act No. 12 of 2011)
The Environmental Management (Licensing) Regulations, 2013

SERIAL NO.: ……………………
LICENCE NO.: ……………………

WASTE MANAGEMENTLICENCE

Holder's name ……………………………………
Adress ……………………………………

The licence relates to handling of general and industrial waste ……………………
in (Province [s]) ……………………

The licence is granted for a period of …………… commencing on the ………… day of ………………………… 20 …………

The conditions of grant of the licence are as shown in the Annexures attached hereto.

Issued at …………………… this …………………… day of ……………………

……………………………………
Director-General

ENDORSEMENT OF LICENCE

This Waste Management Licence has this …………… day of …………… 20 ………… been entered in the Register.

Date and Official stamp — Director-General

Source: The Environmental Management Act no. 12 of 2011

Fig 5: Sample of ZEMA waste management Licence

Project-related E-waste could end up in a landfill site. However, any dangerous waste disposal using this method must be managed under the guidelines prescribed in the regulation's ninth schedule and under section 24 (2) of the requirements for operators at a hazardous waste disposal site. There will be no transboundary movement of project-related hazardous waste.

Environmental Social Standards (ESS)

The project follows national legislation, ESHG, and GIIP for E-waste management. The project avoids E-waste disposal by reuse, recycling, and recovery. Where E-waste cannot be reused, recycled, or recovered, the project will treat, destroy, or dispose of E-waste following the Environmental Management (Licensing) Regulations (SI. No 112 of 2013). When hazardous waste management is conducted by third parties, the project will use Zambia Environment Management Agency (ZEMA)-licensed hazardous waste contractors, and all E-waste will be disposed of in a hazardous waste landfill under the Environmental Management (Licensing) Regulations (SI. No 112 of 2013).

World Bank Safety and Health Guidelines (WB ESHG)

The WB ESHG promotes waste prevention, reuse, and recycling, good housekeeping, inventory control, avoidance of damage, and instituting procurement measures that allow the return of reusable material. It requires the segregation of hazardous waste from other waste, appropriate storage (labelled containers), and record-keeping. It allows collection, transport, and disposal under the Environmental Management (Licensing) Regulations (SI. No 112 of 2013). The ESHG also requires monitoring records for hazardous waste collected, stored, or shipped using the recommended procedures. (Zambia - Southern African Development Community (SADC) Regional Statistics Project P175731).

Good International Industry Practice (GIIP)

GIIP promotes the obligation of distributors to offer consumers a take-back system where E-waste items can be disposed of free of charge. There are two types of take-back systems, and distributors of EEE items must offer one of these schemes to their customers. Examples include a free in-store take-back scheme where distributors accept E-waste items from customers purchasing equivalent new items and distributors' take-back schemes where consumers can dispose of WEEE items free of charge at designated collection facilities. E-waste generators should manage and dispose of E-waste responsibly as mentioned in the preceding paragraphs. Additionally, when purchasing a new electrical item, arrange with the retailer to collect the old one. Businesses and other users (e.g., schools, hospitals, government agencies) of electrical and electronic goods (EEE) must ensure that all separately collected E-waste is treated and recycled.

E-Waste Mitigation Measure and Management/Disposal Plan

This E-waste management plan contains proposed mitigation measures through which all E-waste can be managed under Zambian law, WB ESF, WB ESHG, and GIIP. The mitigation measures or guidelines are designed to avoid, minimize, and reduce negative environmental and social impacts at the project level.

Considerations on Waste Management in Zambia

According to Zambia - Southern African Development Community (SADC) Regional Statistics Project P175731 March 2023, the ZAMSTATS was mandated to manage environmental and social risks and impacts of the project throughout the project life cycle in a systematic manner, proportionate to the nature and scale of the project and the potential risks and impacts. The generation of all forms of waste is one of those risks that was considered during the preplanning, construction, operations, and decommissioning phases of the project. waste management planning for the project was conducted as early as possible to identify sound management practices and procedures all within the country's legal and environmental frameworks. Wastes include hazardous, solid, demolition or construction, clinical and electronic waste. The focus of this plan was on electronic waste or E-waste. The E-waste management plan was implemented throughout the project's lifecycle to protect the environment, safeguard the health of the local communities, and comply with The World Bank Environment, Safety and Health Guidelines (ESHG) and Good International Industry Practice (GIIP).

Electronic waste (E-waste) is a term used to cover items of all types of electrical and electronic equipment (EEE) and its parts that have been discarded, irreparable or at the end of life. Although E-waste is a general term, it is considered to cover laptops, desktops, tablets, TVs, mobile phones, and household appliances. E-waste contains materials that, if mishandled, can be hazardous to human health and the environment, but most importantly, also materials that are valuable and scarce.

Toxicity and radioactive nature of E-waste on the human, water, soil, and animals

Electrical and electronic equipment contain different hazardous materials, which are harmful to human health and the environment if not disposed of carefully. While some naturally occurring substances are harmless, their use in the manufacture of electronic equipment often results in compounds which are hazardous (e.g., chromium becomes chromium VI). Lead, mercury, cadmium, and polybrominated flame retardants are found in electronic equipment and are all persistent, bio-accumulative toxins (PBTs). They can create environmental and health risks when computers are manufactured, incinerated, landfilled, or melted during recycling. PBTs are a dangerous class of chemicals that have longevity in the environment and bioaccumulate in living tissues. PBTs are harmful to human health and the environment and have been associated with cancer, nerve damage and reproductive disorders.

Table 1: Regional Statistics Project P175731 March 2023: selection of the most found toxic substances in E-waste

Substance	Occurrence in E-waste
Halogenated compounds	
PCB (Polychlorinated biphenyls)	Condensers, Transformers
Chlorofluorocarbon (CFC)	Cooling unit, insulation form
Heavy metals and other metals	
Arsenic	Small quantities in the form of gallium arsenide within light-emitting diodes
Barium	Getters in CRT
Beryllium	Power supply boxes which contain silicon-controlled rectifiers and X-ray lenses
Cadmium	Rechargeable NiCd batteries, fluorescent layer (CRT- Screens) printer inks and toner, photocopying machines (Printer drums)
Chromium VI	Data tapes, floppy - disks
Lead	CRT Screens, batteries, printed wiring boards
Mercury	Fluorescent lamps that provide backlighting in LCDs, in some alkaline batteries and mercury mercury-wetted switches

The ways that electronic trash can be disposed of:

There are several ways to dispose of e-waste, which are generally classified as:

Reuse

This refers to restoring and reconstructing already existing systems as well as recycling as much.

Burning

Burning Sometimes it is called smelting. Even though this is a highly hazardous procedure, processing can be completed very cleanly and efficiently to obtain the most precious of metals if.

Dumping

In this process, used containers are filled, a hole is dug, and the material is dumped there. Typically, the site is picked carelessly and could be contaminated in multiple ways.

Disposal

Some businesses in Zambia provide collection and disposal services, or they can handle it on your behalf, either safely or using less cautious people.

Reuse and refurbishment

Although it's usually a good idea if you can, it can be done for less money than dumping. There are numerous meanings associated with refurbishment, such as.

Rebuilding

This refers to taking out outdated electronics, fixing them, and then putting them back in.

Filling

This is the process of packing outdated electrical equipment into containers, mainly as an inexpensive way to get rid of it but also as a means of repairing it.

Repairing

This entails sanitizing, fixing, and simplifying the use of equipment. If the equipment is removed in segments as opposed to in its entirety, this will be considerably simpler to accomplish. Several businesses, including Apple, Samsung, Hisense, Oppo Philips, and others, are experts in repurposing and restoring electrical devices. They are in the greatest position to advise on which equipment and component recycling firms to contact. As you get rid of outdated stuff from your house and yard, you might also find that you can use this space for products that you want to sell.

Electronic waste recycling

Numerous electronic waste items can be recycled, even though a large amount of them is not. E-waste can be recycled in many methods. E-waste may be divided into many waste categories based on the technology being utilized, as well as the material's composition and potential for harm. Reusing electronic waste reduces the number of natural resources needed to create it in the first place (E-waste Management - Faber India). The repurposed electronic trash can be employed in numerous goods, like

Reusable products, Waste-to-energy technologies (such as incineration and combustion), Newer products and new product development.

Electronic waste recycling

According to Earth.Org, E-waste recycling is the process of extracting valuable materials after shredding the e-waste into tiny pieces that could be reused in a new electronic appliance.

Why recycling electronic trash is important

Recycling electronic waste (e-waste) is essential for the design and development of a web-based e-waste management system, as it addresses critical environmental, economic, and health issues associated with the growing volume of discarded electronics. E-waste is now the fastest-growing solid waste stream globally, with an estimated 57.4 million metric tons generated in 2021 alone, and it is projected to increase by three to four per cent annually (Baldé *et al*., 2021). This surge in e-waste poses significant environmental threats due to the presence of hazardous materials such as lead, mercury, and cadmium, which can leach into soil and water sources if not properly managed (UNEP, 2020) [9]. By implementing an effective recycling system, these toxic substances can be contained, thereby reducing pollution and protecting ecosystems.

Moreover, recycling e-waste conserves valuable resources; for example, it recovers precious metals like gold and copper that are often found in electronic devices (Hopewell *et al*., 2009). This not only reduces the need for environmentally damaging mining operations but also contributes to energy savings and lower greenhouse gas emissions associated with production processes (Binns *et al*., 2013). The circular economy model promoted by e-waste recycling emphasizes the principles of reducing, reusing, and recycling, allowing materials to be repurposed rather than discarded (Geissdoerfer *et al*., 2017).

Additionally, engaging in e-waste recycling creates economic opportunities by generating jobs in the recycling sector and supporting local economies through sustainable practices (Baldé *et al*., 2017). A web-based e-waste management system can facilitate these processes by providing a platform for consumers to easily access recycling services, track e-waste disposal, and promote awareness about the importance of responsible electronic waste management. Prioritizing e-waste recycling is vital for environmental protection, resource conservation, and economic growth, making it a key focus for any comprehensive e-waste management initiative.

The advantages of recycling trash electronics

It's an Eco-Friendly Method of Electronic Garbage Disposal: Recycling electronic garbage is the most environmentally responsible choice. Roughly 98% of electronic waste is thought to be recycled. The most dangerous trash that individuals can encounter is e-waste. Therefore, it is essential to dispose of e-waste (H. Ghimire & P. A. Ariya, "E-wastes: bridging the knowledge gaps in global production budgets, composition, recycling and sustainability implications", Sustainable Chemistry). One major cause of pollution is electronic trash. Recycling electrical waste contributes to a clean environment. Reusing instead of throwing away rubbish in landfills is a more efficient method of waste disposal. This is due to the procedure of maintaining the optimal conditions for the electronic waste to optimize its utilization. Consequently, disposing of unwanted electronics through recycling is an economical option. It is also the most efficient method of getting rid of electrical waste.

It Boosts the Value at Market Electronic waste recycling is the responsible course of action. This is so that it can be sold for more money than it would be dumped in a landfill. Recycling electronic waste should therefore be your first option if you need to dispose of it. In the long run, this will save you cash.

It Assists in E-Waste Sorting

E-waste sorting is problematic because it requires multiple pieces of equipment and multiple steps. If you are going to sort electronic garbage, it is best to have an expert facility handle the sorting for you. You'll save time and money by taking this action.

It's a Source for Reusing Old Equipment

Occasionally, mechanical failures of electrical equipment leave you with a device that you no longer need. An additional life for the previous one or a fresh one might be obtained. To replace a part on a newer device, for example, you may utilize the old one.

Electronic devices come in a wide variety of forms. Therefore, recycling electronic waste has a lot of potential applications. Electronic garbage also has a lot of value. It is therefore wise to dispose of electronic waste in the proper location.

3. Research Methodology

The rapid proliferation of electronic devices has led to a significant global challenge: the management of electronic waste (e-waste). The improper disposal of e-waste, which contains hazardous substances such as heavy metals and toxic chemicals, poses dire consequences for environmental sustainability and human health. Despite advancements in e-waste management in developed nations, many regions, including Zambia, face considerable barriers to implementing efficient and sustainable systems (Baldé *et al*., 2017; Forti *et al*., 2020). This research focuses on designing and developing an integrated e-waste management system that harnesses technological innovation, regulatory collaboration, and stakeholder engagement to address these challenges.

An integrated methodology to determine locations for collection nodes over many possible locations was ideal for the project of designing and developing the e-waste management system.

The Agile project management methodology was employed for the software development process due to its flexibility and adaptability, making it well-suited to fast-paced environments and complex projects. Agile Software Development has become pivotal in modern software creation, offering a dynamic approach that supports continuous reassessment and adjustment of plans, techniques, and objectives. By breaking tasks into smaller, more manageable parts, Agile increases efficiency and allows teams to respond quickly to changes and challenges. This iterative process stands in stark contrast to traditional software development methodologies, which often follow a more rigid and linear path, making it difficult to incorporate feedback or adapt to changing project requirements.

Agile was selected as the development approach for this project because it enables incremental delivery of features in short, focused phases known as iterations. Each iteration produces a working version of the software that can be tested, evaluated, and refined before moving on to the next phase. This not only helps maintain momentum in the development process but also allows for regular feedback and continuous improvement, ensuring that the final product aligns closely with the evolving needs of stakeholders.

In the context of designing and developing the electronic waste management system, Agile proved to be an ideal methodology. The system needed to address a complex set of requirements, from the management of waste collection and disposal to tracking environmental compliance and promoting sustainability. Agile's iterative nature allowed the development team to tackle these challenges step by step, refining the system's functionality over time and adjusting features based on real-time feedback from users and stakeholders.

The development process began with the Agile Planning Life Cycle, a crucial phase that laid the foundation for the project. This life cycle included several stages, starting with pre-planning, where the team defined the scope of the project and identified key goals and deliverables. This was followed by planning, which involved creating detailed plans for each iteration and establishing priorities for feature development. Release planning then focused on preparing the system for deployment, ensuring that each iteration was aligned with the overall project timeline. Finally, backlog management ensured that any outstanding tasks or issues were effectively tracked and addressed throughout the development process.

Following the planning stages, the core principles of Agile were applied to guide the development of the electronic waste management system. These principles included Scrum, a popular Agile framework that emphasizes collaboration, accountability, and iterative progress. Scrum helped structure the project by organizing it into "sprints," or short work cycles, during which specific features were developed and tested. Daily stand-up meetings kept the team aligned and allowed for quick problem-solving when challenges arose.

Extreme Programming (XP) was another key principle utilized, focusing on improving software quality through practices like pair programming, frequent testing, and continuous integration. These practices helped ensure that the system was robust, reliable, and capable of meeting the demands of end-users.

Kanban, a visual management tool, was also employed to enhance workflow and increase transparency in the development process. By using a Kanban board, the team could easily track the progress of tasks and identify any bottlenecks that needed to be addressed. This approach improved the overall efficiency of the project and ensured that resources were allocated effectively.

Lastly, Lean principles were applied to minimize waste and optimize the use of time, effort, and resources. This focus on efficiency was particularly important given the complexity of the electronic waste management system, where even small inefficiencies could lead to delays or increased costs.

The final phase of the project involved evaluating the impact of Agile principles on software quality. Agile's emphasis on continuous testing and feedback throughout the development process ensured that the system was thoroughly vetted before deployment. Regular testing allowed the team to identify and resolve bugs early, reducing the likelihood of major issues arising after the system went live. Furthermore, the iterative nature of Agile meant that each new feature was built on a solid foundation, with lessons learned from previous iterations applied to future development efforts.

In conclusion, the use of Agile methodology for the development of the electronic waste management system was instrumental in delivering a high-quality product that met the needs of both users and stakeholders. Agile's flexibility, focus on collaboration and commitment to continuous improvement enabled the project to adapt to challenges and deliver results efficiently and effectively (International Journal of Engineering Applied Sciences and Technology, 2021 Vol. 5, Issue 12, ISSN No. 2455-2143, Pages 73-78).

3.1 Research Baseline

This study employed a descriptive quantitative research design to gather data on the current state of e-waste management in Zambia. A structured questionnaire was distributed among key stakeholders, including the Zambia Environment Management Agency (ZEMA), the Ministry of Health, the Ministry of Technology and Sciences, and members of the public. The sample size was determined using the Yamane formula, ensuring a representative distribution of responses across various demographics.

3.2 Stakeholder Engagement

Surveys and questionnaires were instrumental in identifying critical gaps in existing e-waste management systems. The feedback collected highlighted issues such as limited public awareness, inefficient collection mechanisms, and inadequate regulatory enforcement. These insights were crucial for tailoring the proposed system to meet local needs effectively.

4. Research Finding/Results, Discussion, and Conclusion

4.1 Research Finding/Results

The research identified several critical gaps in existing e-waste management systems:

Limited Public Awareness

A significant portion of the population remains unaware of the risks associated with improper e-waste disposal (ZICTA, 2019) [26].

Inefficient Collection Mechanisms

Current systems do not adequately facilitate the collection of e-waste from consumers (Kiddee *et al*., 2013).

Inadequate Regulatory Enforcement

Regulatory bodies lack the resources and frameworks necessary to enforce existing regulations effectively (Singh *et al*., 2021).

4.2 Discussion

Drawing from global best practices—such as life cycle assessment (LCA), material flow analysis (MFA), multi-criteria analysis (MCA), and extended producer responsibility (EPR)—the proposed system integrates these tools into a cohesive framework tailored to Zambia's socio-economic context. The findings emphasize that combining regulatory frameworks, technological innovation, and stakeholder input significantly enhances the system's effectiveness.

The developed e-waste management system demonstrates the potential for mitigating environmental and health risks associated with improper e-waste disposal. By fostering public engagement and adopting eco-design principles, the system promotes sustainable resource recovery, environmentally responsible disposal, and effective recycling practices. This research underscores the importance of an integrated, multi-stakeholder approach to e-waste management. The implementation of this system could serve as a model for other regions facing similar challenges, contributing to broader efforts in environmental conservation and sustainable development.

Environmental and health effects of e-waste

The ecology suffers because of the serious problem with electronic product trash disposal. It results in the release of hazardous materials into the environment, including dioxins, benzene, mercury, lead, and cadmium (S.H. Ghosh, "Electronic waste management in the Asia Pacific region," Electronic Waste Management). It also pollutes the air, water, and surface. Because of this, they are bad for both the environment and human health. That's why an e-waste management system will be crucial to save the environment, human health, and Zambia's green economy.

Impact on Health

The population's health is seriously threatened by trash. For example, many youngsters are especially susceptible to the risks posed by dangerous metals found in outdated electrical devices. Kids often tend to pick up things that their grownups drop, which increases the possibility that the hazardous substances in the e-waste could hurt them. Toxic materials can also release vapours that might be fatal or cause disease. If exposed to e-waste, anyone could be impacted, though children might be more vulnerable than adults. Diseases like cancer, neurological and reproductive issues, liver and kidney damage, migraines, respiratory issues, and skin diseases can all result from prolonged exposure to harmful compounds.

Environmental Effects

The environment is also at risk from these heavy metals, in addition to the health risks e-waste presents. Hazardous elements such as arsenic, mercury, and lead can leak out of failing electronics and into the recycling process. Some PCBs (polychlorinated biphenyls) are known to cause cancer in humans, and there may be other harmful substances as well. Lead contamination in electronics is a major environmental problem. There's a lot of lead in the components, even though much of the lead in e-waste was discovered in the solder of the circuit boards. Following the disposal of the circuit boards and other e-waste, some lead may have ended up in the environment. Lead, in any form, is toxic to the environment. Headaches, gastrointestinal issues, memory loss, and hearing loss are just a few of the health issues that lead can cause in people. The ecosystem is greatly endangered by mercury, which is also highly toxic. The fact that mercury can reach the water table and build up in fish makes it hazardous to the ecosystem. Comparably, places where a lot of electronics are recycled may see an increase in mercury levels in the air and environment. Environmental harm from arsenic is serious. The body can absorb arsenic from food consumed by humans or animals, and pregnant women and newborns are particularly vulnerable. For soil, plants, and animals alike, it is extremely hazardous. It has also been discovered through certain research that arsenic can contaminate our water table by leaching into the ground.

4.3 Conclusion

The findings from this research underscore the critical need for an integrated approach to e-waste management that incorporates technological advancements and stakeholder collaboration. The proposed system not only addresses existing inefficiencies in e-waste handling but also aligns with global sustainability goals. By fostering public engagement and adopting eco-design principles, this system promotes sustainable resource recovery, environmentally responsible disposal practices, and effective recycling initiatives. The implementation of this integrated e-waste management system could serve as a model for other regions facing similar challenges, contributing significantly to broader efforts in environmental conservation and sustainable development.

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