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Rethinking E-Waste: Environmental Risks, Human Exposure, and the Need for Holistic Policy Reform

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Abstract: ***This paper examines the growing global issue of electronic waste (e-waste) and its adverse environmental and human health impacts. The study identifies significant gaps in safe disposal, recycling, and policy implementation by evaluating current global practices. The paper advocates for urgent legal and institutional reforms based on data from international agencies and academic sources. The findings call for holistic, enforceable policy frameworks supported by education, infrastructure, and global collaboration to manage e-waste sustainably and mitigate associated risks.***

Keywords: e-waste management, environmental health, policy implementation, recycling practices, electronic devices

1. Introduction

The exponential growth of computers, electronic devices, and internet technology has brought significant benefits to society. It has changed how we live, work, learn, socialize, and do business. Many people own and use multiple electronic devices to connect globally. However, the proliferation of such technologies has also precipitated critical global environmental and health challenges. Electronic and Electrical Equipment (EEE) refers to used and end-of-life electronic and electrical products [1]. Electronic waste, often called "e-waste," represents a substantial worldwide health and environmental peril. It encompasses electronic devices or equipment that have been discarded and are no longer needed or functional, or any electronic electrical device that has reached its end of life, whether in good or bad working order [2]. According to the Step initiative, EEE refers to all products with circuitry or electrical components and a power or battery supply. Despite its urgency under the SDGs, EEE is often overlooked or inadequately addressed. Globally, the growing amount of EEE threatens the environment, with incorrect disposal resulting in the release of life-threatening toxic chemicals into the environment and the loss of precious metals [3]. EEE is also considered the most rapidly growing waste in the past decade (3-4% per year), while only 15% is recycled [4]. Although EEE enhances modern living today, it often contains toxic chemicals that negatively impact human health and the environment and fuel the climate crisis.

Although much research has been done on e-waste, many countries are not sufficiently managing the generated EEE. It is also found that more EEE is generated than is being safely recycled in many countries of the world, and more cooperative efforts are needed to tackle the escalating EEE problem through appropriate research and training [5]. Hence, more significant effort is needed to reinforce more innovative approaches. This paper aims to assess the environmental and human health risks of e-waste and propose sustainable policy recommendations based on global practices. The significance of this study lies in its comprehensive approach to addressing policy gaps, health impacts, and economic losses associated with e-waste, especially in developing countries where regulatory enforcement is weak.

2. Research Methodology

This review used a methodical approach to find, pick, and compile relevant studies on e-waste management and its effects on the environment and human health. The literature review used a variety of sources, including peer-reviewed scholarly journals, official reports from international organizations (WHO, UN, EPA), government publications, industry environmental reports, and institutional studies. Sources were identified through scholarly literature searches, official company websites, and policy document repositories. While it included important works on e-waste management, the study prioritized current publications (2013–2024).

The identified sources were grouped into the following major themes using the thematic synthesis analytical approach: sources of e-waste generation, environmental impacts, risks to human health, economic implications, and policy recommendations.

The Source of EEE

Many sources of EEE are generated from industries, ranging from different categories, such as electrical, communications, information technology, and portable devices. It consists of various materials and hazardous substances, including iron. It can be classified into several categories, including household appliances, IT and telecommunication equipment, and consumer electronics [6]. When EEE reaches the end of its

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lifecycle, it becomes electronic waste (e-waste). A total of 54 different product types are classified as e-waste, and these are grouped into six categories: large equipment, small equipment, temperature exchange equipment, screens and monitors, small information exchange equipment, and lamps [7]. Table A below summarizes a few of the product types.

Table A: List of E- Waste Generated

• Central Processing Units (CPU) Monitors	• Office Equipment, (Photocopiers, Projectors	• Air Conditioners
• Laptops	• Dictating Machines	• Washing machines
• Printers	• Peripherals: UPS, Scanners	• Refrigerators
• Mobile Phones	• Used Electronic Cables	• Stoves
• Satellite Equipment	• Photographic Equipment	• Hair dryers
• Tablets	• Wireless headphones	• Microwave cookers
• Switches	• GPS devices	• Electric Cookers
• Routers	•	• Air Conditioners
• Electronic devices	•	• Electronic Toys

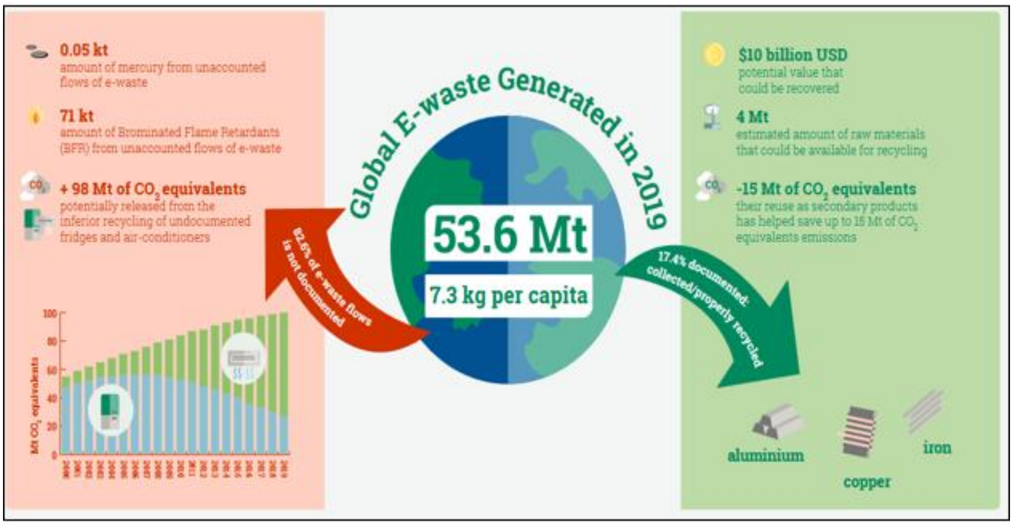

Figure 1: Global E-waste Generated
*Source**:** The Global E-waste Monitor-Quantities, flows, and the circular economy potential*

The trend of e-waste generation continues to increase globally. In Figure 1 above, the Global E-waste Monitor 2019 notes that the world generated 53.6 million metric tons (Mt), with only 17.4% properly collected and recycled. E-waste generation is projected to escalate to 74.7 Mt by 2030. Asia, leading in e-waste production, generated 24.9 Mt in 2019, followed by the Americas (13.1 Mt), Europe (12 Mt), and Africa (2.9 Mt). Europe recorded the highest per capita e-waste generation at 16.2 kg, trailed by Oceania (16.1 kg) and America (13.3 kg). Sixty-two million tonnes (62 Mt) of e-waste were produced in 2022 [8]. According to The Global E-waste Monitor 2020, Africa generates 2.9 million tons of e-waste yearly, yet only 1 percent is collected or recycled officially. A few countries, such as South Africa, Morocco, Egypt, Namibia, and Rwanda, have e-waste. Ghana has some Technical Guidelines on Environmentally Sound E-Waste Management for Collectors, Collection Centers, Transporters, Treatment Facilities, and Final Disposal that have been developed and are not being enforced. Nigeria and Kenya are still very reliant on informal recycling. There have been some improvements, but not many, in the legal, institutional, and infrastructural framework for achieving sound management of e-waste in some countries. Unfortunately, some USD 3.2 billion worth of raw materials are contained in e-waste generated in Africa. Much economic value is lost, and a cost is incurred for the environment and society.

A study conducted in Nigeria shows that approximately 60, 000-71, 000 tonnes of used EEE were imported annually into Nigeria through the two main ports in Lagos in 2015 and 2016. It was found that most of the imported EEE were used and shipped from developed countries such as Germany, the UK, Belgium, the USA, etc. A basic functionality test showed that, on average, at least 19% of devices were non-functional [9]. The resulting statistics of EEE highlight the implications and the importance of policymakers' attention and the need for holistic approaches. Global EEE production reached a record of 53.6 million metric tonnes in 2019, a 21% rise from 2014, and is expected to reach 74.6 million metric tonnes by 2030, according to a Global E-waste Monitor study in 2030 [10]. Other research conducted by the United Nations University estimated that the generation of EEE by businesses

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and industries worldwide has exponentially increased [11]. The manufacturing industry is also a significant source of EEE due to the frequent replacement of electronic equipment during upgrading production processes [12]. In 2022, an estimated 62 million tonnes of EEE were produced globally. Only 22.3% were documented as formally collected and recycled [13].

3. Economic Value of E-Waste Generated

In the recycling process, valuable and non-valuable materials and metals are taken without damaging their properties, or converted into valuable products by reducing the effect they may create. If they are non-recyclable, they will be thrown away. After some time, the materials can release volatile substances into fumes in the air, a leaching organotin; both affect health and environmental ecosystems [14]. As depicted in Figure 2, when EEE is adequately recycled, substantial economic monetary values can be gained and used to offset the recycling cost. According to The Global E-waste Monitor 2020, Africa generates 2.9 million tonnes of e-waste annually, yet only 1 percent is collected or recycled officially. Some USD 3.2 billion worth of raw materials are contained in e-waste generated in Africa. Much economic value is lost, and the environment and society are impacted [15]. Many materials can be recovered from EEE, including precious metals, iron, glass, steel, plastics, etc. Recycling also reduces the burden on the producers by giving them back the resources needed to reproduce the products [16]. EEE can contain up to 69 elements from the periodic table, including precious metals (e. g., gold, silver, and copper from mobile phones, PCs, etc., Platinum, palladium, ruthenium, rhodium, iridium, and osmium), and Critical Raw Materials. (CRM) (7) (e. g., cobalt, palladium, indium, Germanium, bismuth, and antimony), and noncritical metals like aluminum and iron. A study in 2015 analyzed the potential recovery value of 14 products using e-waste volume in that year and the prediction of e-waste volume in 2020. The highest possible revenue in 2015 was 528 M€, given by CRT monitors. As the years change, the number of individual products, depending on technological development, changes [17]. In 2020, the highest potential revenue was contributed by smartphones at a value of 746M€. Other research projects that cell phones will contribute the most revenue in 2030 (15, 777 M€), while smartphones will come in second place with a total value of 2, 306 M€. [18].

Figure 2: Economic Monetary Values in EEE
Sources: The Global E-waste Monitor 2020-Quantities, flows, and the circular economy potential

4. Environmental Impact of EEE

Research shows that soil, water, air pollution, and ecosystems are frequently prevalent. Improper disposal of EEE in landfills results in water and soil contamination and climate change. Health dangers from incorrect electronic waste disposal and illegal recycling methods are particularly high for communities near the disposal facilities. The World Health Organization (WHO) reports that exposure to potentially harmful compounds during the reuse and recycling of e-waste might result in neurological problems, respiratory and skin ailments, and even cancer development

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[19]. Toxic substances from E-waste can contaminate soil and groundwater, affecting agriculture and causing the pollution of drinking water sources. E-waste contains several toxic additives or hazardous substances, such as mercury, brominated flame retardants (BFRs), chlorofluorocarbons (CFCs), or hydrochlorofluorocarbons (HCFCs).

1) Human Health Risk and Environmental Hazard of EEE

Air Pollution, such as open burning of E-waste, releases harmful dioxins and furans into the atmosphere, contributing to respiratory issues and environmental degradation. Research shows that occupational and environmental exposure is also present. Further, children are also at risk from additional routes of exposure. Lead is a common substance released into the environment when e-waste is recycled, stored, or dumped using informal activities, including open burning. Informal e-waste recycling activities may have several adverse health effects. Children and pregnant women are particularly vulnerable [20]. The children can be exposed to informal e-waste recycling sites as they play nearby. Previous research also shows that adults and children can be exposed by inhaling toxic fumes and particulate matter, through skin contact with corrosive agents and chemicals, and by ingesting contaminated food and water.

Some hazardous chemicals can be passed from mothers to children during pregnancy and breastfeeding. According to statistics from the World Health Organization, between 2.9 and 12.9 million female practitioners and approximately 73 million children are involved in informal recycling of solid waste. Young children playing outside or in nature frequently put their hands, objects, and soil in their mouths, increasing the risk of exposure [21]. Toxic chemicals are a significant cause of disease in Latin America. Thousands of new chemicals and pesticides have been invented and spread into the environment over the past 50 years [22]. It is essential to realize that groundwater, various metals such as mercury, lead, and arsenic are released, which proves to be very dangerous to the health of the communities in that region that rely on the water sources. These contaminants can bioaccumulate in fish and other species of water ecosystems, be transmitted through the food chain, and negatively impact human health.

According to the Environmental Protection Agency (EPA), a U. S. federal agency responsible for protecting human health and the environment by developing and enforcing environmental regulations, note the benefits of becoming a certified recycler. It notes that responsible electronics recycling provides essential benefits, such as reducing ecological and human health impacts from improper recycling and increasing access to quality reusable and refurbished equipment for those who need it, further, reducing energy use and other environmental impacts associated with the mining and processing of virgin materials, and conserving our limited natural resources. Implementing a study of the R2 & e-Stewardship recycling standard is important [23]

2) Water Contamination of EEE

It has been found that a significant amount of lead and cadmium ions from the broken cone glass of cathode ray tubes and other electronics can mix with water and turn it acidic, which is a common occurrence that affects groundwater. The level of cadmium contamination is higher than the regulatory threshold, indicating serious toxicity problems in the groundwater system. The contamination is offensive and harms the ecosystems and the surrounding population [24].

3) Safe Recycling Process

Electronic garbage, or e-waste, recycling, and disposal are critical for environmental sustainability and human health. E-waste comprises abandoned electronic devices and components such as cellphones, computers, and circuit boards that may include dangerous elements such as lead, mercury, and cadmium. Process begins with collection and sorting, which involves gathering and categorizing e-waste to ensure that valuable elements can be recovered [25]. The devices are then disassembled and shredded into smaller components. This step removes valuable materials such as precious metals and polymers for reuse. To prevent environmental pollution, dangerous substances must be appropriately disposed of. Furthermore, some e-waste components can be reconditioned, resold, or donated to extend their useful life [26].

5. Summary of Findings

The paper identified important areas, such as the source of global EEE, the human and environmental impact, economic value, safe disposal practices, and the need for a holistic approach to policy campaigns and implementations. This study's findings emphasize the critical need for proactive measures to mitigate the adverse impacts of e-waste on global health and the environment. Best practices for e-waste should include collection, transportation, pre-sorting, dismantling, and separation of all e-waste components. Formal recycling, reprocessing, recovery, and final safe disposal of the e-waste for maximum residual value benefits. It should be recycled with national environmental regulations, international best practices, and environmentally sound management. Policy Implementation to achieve targets is essential. It includes legislation for improved monitoring of the quantities and

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flows of e-waste. It is necessary to achieve targets. By reducing e-waste generation, promoting recycling, promoting safe disposal, and quantifying generation, we can encourage recycling, promote safe disposal, and quantify the challenges according to Global EEE recommendations.

6. Policy Implications and Future Directions

The outcome of the research suggests that policies should be reinforced. Enforced monitoring of the quantities and flows of e-waste is essential for evaluating and monitoring developments over time to set and assess targets. Sound policies and legal instruments can only be developed with better e-waste data. Understanding the quantities and flows of e-waste provides a basis for monitoring, controlling, and preventing illegal transportation.

1) Holistic Approach to Policy Implementation

The government should establish a clear policy on compliance and a legal framework for collection and recycling. It is crucial to introduce extended producer responsibility and partnerships and establish finance for collecting and recycling e-waste. Further advocate for policies integrating environmental protection, public health, and socioeconomic considerations, ensuring a comprehensive response to hazard management of EEE. Procedures like transporters, treatment facilities, final disposal, and certifications are developed and enforced. Standards, such as the regulation of EEE stewardship, should be adhered to. International standards, including the Certificate of Responsible Recycling and other guidelines, should be strictly enforced, followed, and audited. A certificate of proof of commitment from recycling bodies is developed and implemented.

2) Policy Recommendations Best Practices for Data Security

Effective management of e-waste and data security is imperative. With the growing number of cybersecurity threats, setting policies and technical procedures to dispose of sensitive data from EEE is essential. Data security should be cleaned from data-bearing devices and removed from all media. This includes hard drives and SSDs, as well as degaussing. They should be crushed or shredded according to international standards such as IT Assets Disposition (ITAD) regulations and data security.

3) Advocacy to Reduce EEE Generation, Promote More Recycling

There must be advocacy to reduce EEE generation, promote more recycling, and set collection and recycling targets. Additionally, adequate financial resources should be allocated, and dumping and emissions should be prevented. Further, the government should create green jobs to reduce environmental impact while promoting sustainable development. Recycling, conserving waste management, and establishing priorities for policymakers to influence regulations are essential.

7. Recommendation For Environmental Protection and Education

Promoting sustainable development through continuous education through public awareness campaigns and incentives, public awareness campaigns, and incentive programs is essential. Encouraging the recycling and reuse of EEE supports sustainable resource management and aligns with the United Nations Sustainable Development Goals (SDGs) [[27]]. Having regulations and a comprehensive policy framework for recycling practices is imperative. Especially educating citizens on how it impacts society, health, and the environment. It reduces pollution through stronger recycling practices, rules, and a regulatory framework by the government to reduce health hazards. Reinforce the implementation of the Basel Convention and the European Union Waste of Electronic and Electrical Equipment (WEEE) Directive in 2022. To achieve maximum impact, policymakers should ensure regular auditing of environmental agencies, recycling companies, and manufacturing companies responsible for operating without significant negative ecological consequences.

8. Conclusion and Future Research

The global demand for consumer electronics and the widespread adoption of digital technologies have led to an exponential increase in the generation of electrical and electronics waste (e-waste) [28], with annual e-waste generation reaching more than 62 million tonnes per year in 2022 [29]. This study reinforces the urgent need for global regulatory harmonization in e-waste management, emphasizing the interconnected environmental, health, and economic concerns that demand immediate attention.

The analysis reveals profound implications of improper e-waste recycling, particularly the severe environmental and health hazards posed by inadequate disposal practices. With EEE comprising discarded devices containing hazardous materials that threaten both environmental sustainability and human health, the proliferation of electronic technologies has created critical global challenges that extend far beyond waste management. The limited safe recycling infrastructure, with only 22.3% of global e-waste formally collected and recycled, underscores the magnitude of this crisis [30].

E-waste management presents both significant challenges and promising opportunities. While rapid growth, complex composition, informal recycling practices, and inadequate infrastructure create substantial barriers, the potential for

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resource recovery, circular economy adoption, technological innovations, extended producer responsibility (EPR), and green job creation offers pathways toward sustainable solutions. The call for a holistic and enforceable policy framework is not merely timely—addressing this global challenge's multifaceted nature is essential.

Effective e-waste management is crucial for achieving multiple Sustainable Development Goals (SDGs), particularly those related to environmental protection, health, and sustainable consumption and production. The integration of technological innovations, comprehensive public education, and responsible corporate practices must serve as the foundation for sustainable e-waste solutions that unlock the potential for responsible resource usage while mitigating environmental and health risks [31].

9. Future Research

Due to the complexities and ambiguities of the recycling practices of EEE being tenacious and rather human-intensive, involving sorting, recycling, and separation, in some cases, precious materials are lost. The current inadequacies in recycling systems lead to substantial losses of valuable raw materials, contributing to resource wastage [32].

Future research should prioritize developing and implementing AI and robotics technologies to enhance processing efficiency and accuracy in large-scale environments. Apple's innovative disassembly robot technology, exemplified by Daisy's capability to process 200 iPhone devices per hour while recovering millions of dollars worth of materials, demonstrates the transformative potential of advanced recycling technologies [33].

Research priorities should focus on scaling such technological solutions globally, developing cost-effective automation for diverse e-waste streams, and creating integrated systems that combine technological innovation with robust policy frameworks to achieve comprehensive, sustainable e-waste management solutions.

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