GSJ: Volume 12, Issue 6, June 2024, Online: ISSN 2320-9186
www.globalscientificjournal.com

ADDRESSING ELECTRONIC WASTES CHALLENGES: EFFICIENT TOOLS AND APPROACHES FOR REDUCTION

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ABSTRACT

The global increase in demand for electronic products which gives rise to increasing e-waste generated per annum coupled with its associated environmental and health problems resulting from improper management and disposal necessitated this research. The hazardous nature of Electronic waste (e-waste) due to its components and rapid increase in its generation makes it a global concern, posing significant environmental and health risks. This study aims to address the challenges associated with the tremendous increase in e-waste generated all over the world and proffering effective approaches for mitigating its adverse environmental and health impact. Key focus include. Global e-waste generation, environmental impact of e-waste, E-waste management practices, and e-waste regulatory framework. Results of the review reveal that reusing, refurbishing, repairing, recycling, developing policy recommendations and administer trainings for stakeholder are current and effective solutions to minimize e-waste generation.

KeyWords
E-waste, recycling, electronic products, sustainable management, environmental policy, circular economy.

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1.0 INTRODUCTION

The hazardous nature of Electronic waste (e-waste) due to its composition and components makes its handling, management and disposal critical to ensuring human and environmental health and safety, as some major environmental pollution and poisoning around the world can be associated with improper disposal/management of such waste. The inability of some e- wastes to decompose over long period makes its disposal challenging especially in developing countries where burning, burying and disposal into water bodies are common practices posing serious health risk to the environment and humans. By definition E- waste are electrical or electronic equipment such as mobile phones, computers, TVs, fans, washers, and dryers that have been abandoned or discarded after the end of useful life [33].

Roughly 17.4% of the electronic garbage produced worldwide in 2019 was recycled or disposed of appropriately. But since it wasn't recorded, what happens to the remaining 82.6% might be disposed of without enough care or recycling. The massive demand for electronic items in modern life makes the global development of e-waste imperative. E-waste management calls for effective methods and strategies since it contains a number of hazardous substances, including halogenated compounds that are toxic to humans, micro-organisms, and plants, such as polychlorinated biphenyls (PCBs), tetrabromobisphenol A (TBBPA), and polybrominated biphenyls (PBB) [33]. E-waste contains a variety of dangerous materials, such as lead, mercury, and brominated flame retardants. Biological approach is more environmentally friendly than conventional methods for removing metals from e-waste because it doesn't require additional treatment or produce secondary contamination. The foundational information necessary for this research was gathered from books, academic journals, and online articles sourced from the websites of internationally recognized organizations specializing in e-waste management. Conceptual information needed for this research was also gathered from books, Journals and online articles obtained from web pages of internationally recognized organizations in e-waste management.

2.0 METHODS

Using searches on academic research publication databases like PubMed, Science Direct, and Google Scholar, a compilation of peer-reviewed articles on e-waste from the past 10 years was made possible. We obtained publications, reports from governmental and regulatory agencies, and directions via official and informal channels. The literature was searched using the following keywords: e-waste, used electronic equipment, e-waste management, circular economy in e-waste management, and e-waste norms and recommendations.

3.0 OBJECTIVES

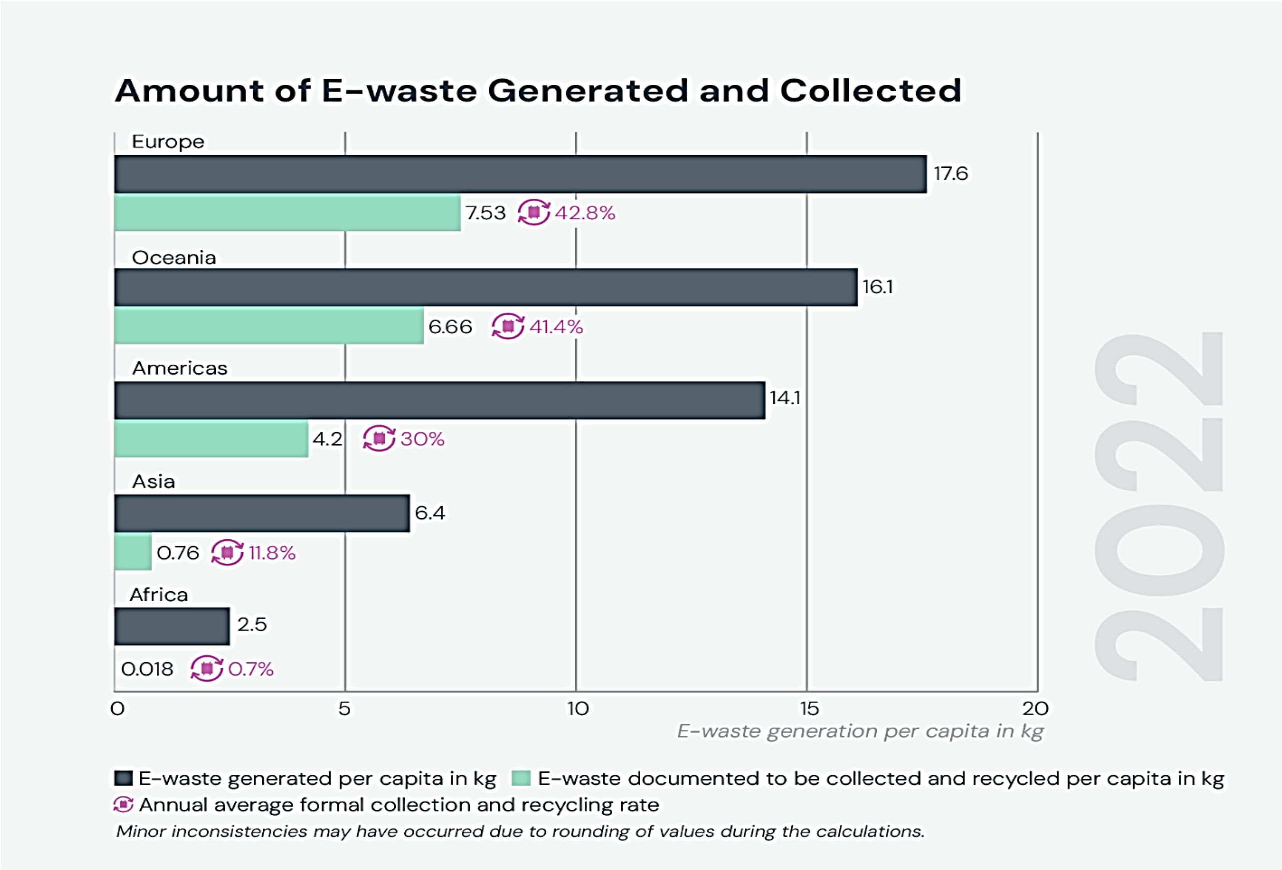
- To assess how e-waste is currently being generated worldwide.
- To examine how inappropriate e-waste management affects the environment and human health.
- To determine environmentally friendly e-waste handling techniques and technology.
- Examine current E-waste regulatory structures.

4.0 LITERATURE REVIEW

4.1 Global E-Waste Generation

E-waste stands out as one of the fastest-growing waste streams worldwide, as noted by various sources. In 2016, it amounted to a staggering 44.7 million tonnes. By 2018, this figure had surged to an estimated 50 million tonnes, earning it the moniker 'tsunami of e-waste' from the UN. The annual value of this waste stream is conservatively estimated at $62.5 billion. Forti et al. (2020) highlighted that excluding photovoltaic panels, e-waste generation reached approximately 53.6 million metric tonnes in 2019, with a per-capita generation rate of 7.3 kg. Projections suggest that by 2030, e-waste generation could surpass 74 million tonnes. The trend indicates a significant increase in the generation of temperature exchange equipment, followed by large equipment and small equipment along with lamps. In terms of regional distribution, Asia led with 18.2 Mt of e-waste in 2016, followed by Europe (12.3 Mt), America (11.3 Mt), Africa (2.2 Mt), and Oceania (0.7 Mt). Surprisingly, Oceania had the highest per capita e-waste generation at 17.3 kg per inhabitant, with a mere 6% of e-waste being collected and recycled. Europe followed closely behind with an average of 16.6 kg per inhabitant, but with a higher collection rate of 35%. In contrast, America generated 11.6 kg per inhabitant, with only 17% of e-waste collected, similar to the collection rate in Asia (15%). Africa's per capita e-waste generation was notably lower at 1.9 kg per inhabitant, with limited data available on its collection percentage.

By 2022, the generation of e-waste around the world had risen to at least 3. 4%, reaching 59. 4 million tonnes. The total of e-waste generated and never recycled on earth by the end of the year 2022 was found to be more than 347 million tonnes. While the cross-national mobilization of e-waste has generated awareness among the citizenship, no global surveys have so far been made on the volumes and trade arteries. However, in 2019, around 5 percent of the data had the number at the start of the message-identifier. 1 million tonnes out of e-waste of over 50 million-tonne annual generation, was reportedly exported across borders; it was below 10 percent. Also, according to the study, global e-waste production reached 62 million tonnes in 2022, which is a higher 82% production as compared to 2010. Estimates for this have pointed to a projected increase to 82 million tonnes by the year 2030. However, even with these statistics, only one percent of the demand for individual rare earth elements is fulfilled by e-waste recycling[47].



(Source: Global e-Waste Monitor 2024).

5.0 CATEGORIES AND CHEMICAL COMPOSITION OF E-WASTE

5.1 Screens and Monitors

Equipment like computer monitors, television, laptops, tablets, and notebooks are included in this category

5.2 Temperature Exchange Equipment

Some of the appliances include those that offer cooling systems, freezing systems, and heating systems, including freezers, air conditioners, coolers, refrigerators, and heat pumps.

5.3 Lamps

This group includes fluorescent lamp, LED lamp, compact fluorescent lamp, xenon arc lamp, filament lamps and. high-intensity discharge lamps (HID).

5.4 Small Equipment

This category is very extensive and encompasses many pieces of equipment that are found not only in the kitchen but also in other areas. It incorporates the usual household eeuipment such as microwave ovens, vacuum cleaners, electric cookers, toasters, electric kettles, and even weighing machines. Further, it also includes devices like radio, video camera, several electrical and electronic tools, small monitoring devices, control devices, and even some small medical instruments.

5.5 Small Information Technology and Telecommunication Devices

This category encompasses compact information technology and telecommunication devices such as smartphones, mini calculators, smart watches, routers, modems, personal computers, and compact printers, landlines, and GPS devices.

5.6 Large Appliances

This category comprises large appliances such as dishwashers, washing machines, clothes dryers, large copiers, printers (Xerox machines), and photovoltaic panels commonly found in both households and offices.

Table1.Chemical Composition of E-Waste

SN	Component	Types	Examples
1	Inorganic compounds	Toxic metals	Barium, Beryllium, Cadmium, Cobalt, Chromium, Iron, Lithium, Lanthanum, Mercury, Manganese, Molybdenum, Nickel, Silver, Chromium, Antimony, Arsenic, Aluminium, Selenium, Bismuth, Zinc etc.
		Rare metals	Yttrium(Y), Europium(Eu)
2	Organic compounds	Halogenated compounds	Chlorofluorocarbon(CFC), Polycyclic aromatic hydrocarbon (PAH),phenols, phthalate esters, Organo-phosphorous, Polychlorinated biphenyls (PCBs), Brominated and Chlorinated benzenes, : Poly brominated biphenyl (PBB), etc.
3	Plastics		Poly Vinyl Chloride (PVC), Plasticizers
4	Compounds of most concern		Liquid crystals from LCDs, Toner dust from Toner cartridges, Nanoparticles, PC-boards, batteries CRTs, LCDs, plastics, PCB-containing capacitors, toner cartridges, mercury containing component

(Source: Diane et al, 2020)

6.0 ENVIRONMENTAL AND HEALTH IMPACTS

Inadequate control, treatment or dumping of e-waste bears negative implication on the environment and people; hence, actors have a vital function to perform.

6.1 Pollution of the Soils and Water

Soil and water pollution arising from the ill management of e-waste is an issue that has appeared all over the world. Computer disposal on dumpsites results in leachate generation which is thereafter discharged into the groundwater system, and this has severe impacts. For example, in Guiyu, Hong Kong which is known to harbour a number of firms involved in the Illegal processing of e-waste, water scarcity has arose from water pollution. This contamination is as a result of dumping of recycling byproducts like, acids and sludge into rivers hence leading to transportation of water which is often considered to be taken from distant areas. It is rather shocking to point out that one cell phone battery contains such a high density of cadmium that it takes only one cell phone battery to pollute a great deal of water.

Additionally, the implementation of processing tools in the industries or other EEE disposal sites may lead into the water bodies which include the surface water as well as the ground water. This contamination has a negative impact on the lives of living organism in water bodies resulting in changes such as acidification, loss of bio-diversity and ecological imbalance. Lead, barium, mercury, lithium and other HM s go into the groundwater by improper disposition, compounding the water pollution when the contaminated rain water joins. [19].

Research done in other countries reveals that the level of contamination of soils and water sources mostly arise from the processing of e-waste. In Vietnam, previous studies found a spike in the concentration of dioxin compounds in the soil of e-waste processing area, which is much higher than the concentration permitted by the WHO regulations. This mainly occurs through activities such as open burning and dumping of waste [23].

6.2 Air Contamination

E-waste disposal through incineration exposes the environment to dangerous gases and pollutants hence extensive pollution. Besides local effects or environmental and health degradation, open-air burning affects large portions of the earth’s atmosphere and moves pollutants to different parts of the world. For example, during the burning of PCB and other plastics components used in the electronics, they release highly toxic dioxins and furans which are a threat to the vital ecosystem component [19]. In the regions where open burning takes place, a variety of e-waste components rises as dust or fumes and becomes the most dominating delivery mechanisms for human with inhalation, ingestion, dermal exposure. Experiments show that the HFRs and PCBs from the recycling sites of e-waste influence the bioaccumulation in wildlife [37]. Also, the incorrect e-waste management has potential effects on air quality with impacts such as depleting the ozone layer and enhancing global warming effects as stated by [38]. The collection of raw materials from e-waste involves some processes that let out greenhouse gases into the atmosphere. Other gases contributing to the increase in temperature of the Earth are chlorofluorocarbons (CFCs) which are used in refrigerators and other temperature exchange equipment which wholesomely affects the ozone layer, a shield. This leads to admission of dangerous ultraviolet light which leads to diverse diseases such as cataracts, vulnerable immune system, skin tumor among others. Moreover, the management of cooling and freezing equipment led to the discharge of 98 million metric tonnes of carbon dioxide equivalents to the environment [35].

6.3 Health Impacts

The lack of processing of electronic waste (e-waste) entail severe impact with a trajectory that goes beyond the physical well-being of human beings [39]. Ingesting food produced from plants grown in e-waste affected earth also has its damages on human health in a more indirect way [40]. Acid leaching similar to open incineration gives out toxic gaseous products that lead to sudden deaths or chronic respiratory-related diseases to workers and residents [41], [42]. Such toxic e-waste elements if ingested can penetrate the body tissues and linger in the fat bulk thus posing health risks on the people dwelling close to unstandardized e-waste disposal site [15]. Furthermore, there are potential concerns such as secondary exposure to the substance in other regions based on the evidence of organic pollutants' long-range transportation [43]. For example, loss of soil fertility because of soil pollution by dangerous metals affects the food chain. Moreover, metal exposure changes the genetic codes and causes diseases such as cancer, thus, is genotoxic in its impact. High risks are experienced by the vulnerable individuals such as: children, pregnant women as well as the workers in the processing facilities. China, Peru, Ghana, Nigeria, India and Pakistan are some of the countries on the receiving end from developed countries in the disposal of e-waste [44].

The discharge of e-waste into the atmosphere harms all living beings positively. The poor management of e-waste poses a threat to anything that has a likelihood of interacting with it. Large amounts of e-waste and products containing metals and other hazardous substances are dumped carelessly in fields by the rivers, wetlands, rivers, and irrigation channels without recycling. High magnitude and random dumping and landfill contribute much to water source pollution. Vegetation is affected by soil pollution through open field dumping with adverse effects on grasses, herbs, plants, shrubs, trees, and cash crops. In the process of incineration of electronic waste, fumes, fly ash, and fine particles containing some toxic chemicals are released to the atmosphere; when inhaled hazardous impacts on human and animal lives may occur [45].

7.0 E-WASTE MANAGEMENT PRACTICES

The introduction of the waste electric and electronic equipment (WEEE) directive (Directive 2002/96/EC), which is anticipated to reduce the disposal of such waste and enhance environmental quality, has advanced the management of e-waste.

7.1 Circular economy

The Circular economy strategies for managing e-waste emphasize extending the lifespan of electronic devices through professional refurbishment or repair and recycling to minimize waste.

7.2 Physical Methods

- **Landfills and Controlled Dumps**

Sanitary landfills are often utilized in dealing with e-waste and sequestration is made to avoid the flow of hazardous liquidation products. Controlled dumps in particular pertain to an ability whereby the arranging of cells is not a necessity.

- **Reuse, Remanufacturing, and Refurbishing**

Waste recycling is one of the concepts in waste management, which is advantageous to the environment and complements simple waste collection. A recent study on the Life Cycle Assessment (LCA) comparison of EOL computer treatment chains in Belgium revealed that take-back obligations put to manufacturers are favorable and stated the significance of an effective collection system. Lesser-known facts have emerged that show that remanufacturing and refurbishing practices are proving to be very environmental and economically viable especially among the photocopier OEMs in Japan [48].

- **Incineration at high temperatures:**

Pyrometallurgical process is one of the most prevailing e-waste handling methods, where components are burnt at high temperatures to recover energy and heat besides dealing with the volume problem. But disadvantage of this method is the release of dangerous toxins which pollutes the environment. Open burning without any control over the emission is a threat.

- **Thermo-chemical Methods:**

Techniques such as gasification, and pyrolysis are less hazardous to the environment as compared to the conventional thermal processes due to the high temperatures, and restricted supply of oxygen to the e-waste [52].

7.3 Chemical/Hydrometallurgical Methods

- **Acid Bath**

Circuit boards are exposed to acidic solutions to recover metals over a defined length of time [51].

- **Electrokinetic Remediation (EKR)**

According to Ding et al, 2021, Electrokinetic Remediation (EKR) involves the application of electric field to the contaminated soil/sediment, enriching the pollutants to the cathode or anode zone through electroosmosis and electromigration.

- **Hydrometallurgical Etching:**

Chemical compounds like HCl, $FeCl_3$ or $CuCl_2$ are employed for washing metals using hydrometallurgical etching [48].

7.4 Biological Methods

- **Bioattenuation and Bio-Augmentation**

Microbes are selected from the remediation site (those that grow well in the contaminated sites), cultured or genetically modified, and then returned to the remediation sites in bio augmentation. In contrast, in bioattenuation, physical/natural phenomena and chemical reactions are used to promote the growth and activity of the microbes in the chosen polluted sites [50].

- **Phytoremediation**

Plants are used in phytoremediation to collect, store and/or decompose contaminants from the soil. As a result, it is taken into consideration as a potential technique for cleaning up e-waste contaminated places. Another effective method would be utilizing microbes, individually or in consortia to bioremediate the e-waste contaminated site without the use of harsh chemicals [53].

8.0 E-WASTE REGULATORY FRAMEWORK

- **Extended Producer Responsibility (EPR):** EPR is a policy framework that emphasizes the responsibility of producers, especially in the management of their products in the post-purchase phase. This approach encourages manufacturers to incorporate environmental considerations into their product design and manufacturing processes. In doing so, it encourages the prevention or reduction of waste at source, improves choice of materials, encourages support for community recycling and recycling programs and as a result, EPR ensures that pro-environmental transactions are achieved throughout the product life cycle [57].

- **Basel Convention (Global):** The number one goal of the Basel Convention is safeguarding human health and the surroundings from the unfavorable results of unsafe waste. Its scope includes a big selection of wastes labeled as "unsafe waste" primarily based on their starting place and/or composition, which includes "different wastes" consisting of household waste and incinerator ash. The Convention objectives to reduce the generation of unsafe waste and sell environmentally sound control practices, no matter the disposal location. It additionally regulates the trans boundary movement of risky wastes, permitting such moves simplest while compliant with ideas of environmentally sound management [54].

- **Stockholm Convention (Global):** The Stockholm Convention goal is the reduction or elimination of persistent organic pollutants (POPs), which pose risks to human health and the environment. Concerns had been raised about the improved degrees of certain POPs in e-waste, particularly in regions where e-waste is incinerated or subjected to harmful strategies, highlighting the pressing need for action by means of governments [55].

- **Bamako Convention (Regional):** Ratified by way of Member States of the Organisation of African Unity, the Bamako Convention got here into effect in 1998 with a focal point on banning imports and regulating the movement of unsafe wastes within Africa. It addresses gaps left by the Basel Convention and prohibits all waste imports without exceptions, offering a sturdy mechanism to cut down the change of hazardous waste to much less evolved countries [56].

- **Minamata Convention (Global):** A United Nations treaty with several signatories and parties, the Minamata Convention ambitions to shield human fitness and the environment from mercury emissions and releases due to human sports. Mercury, prized for its precise homes, is substantially utilized in numerous industries, inclusive of the manufacturing of electrical and digital merchandise.

The Convention outlines measures spanning the complete lifecycle of mercury, along with controls and discounts throughout numerous merchandise, industries, and methods that involve mercury use, launch, or emission [58].

9.0 ENGAGING THE PUBLIC IN RESPONSIBLE E-WASTE MANAGEMENT

Despite the presence of law, gaps persist in public expertise and recognition of e-waste management and control. It is essential to gauge the know-how and attention tiers of electronic product purchasers, who are the number one e-waste generators. The first step toward making such a run involves setting up Specific, Measurable Achievable, Realistic and Time-sure goals which are both short term and long term goals. These goals are the stepping stones in e-waste management awareness campaigns to achieve something concrete.

10.0 CONCLUSION

To sum it up, the current surge in global demand for electronic gadgets has caused a corresponding surge in their e-waste production; this in turn has brought about weighty environmental and health challenges mainly due to insufficient management and disposal methods, therefore necessitating a worldwide engagement on the subject as a matter of urgency. Beyond that point, what emerges from this overview is how embracing practices that promote sustainability like reusing, refurbishing, repairing and recycling electronic items is valuable. ..

Acknowledgment

The author wish to thank everyone that contributed to the success of this work.

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