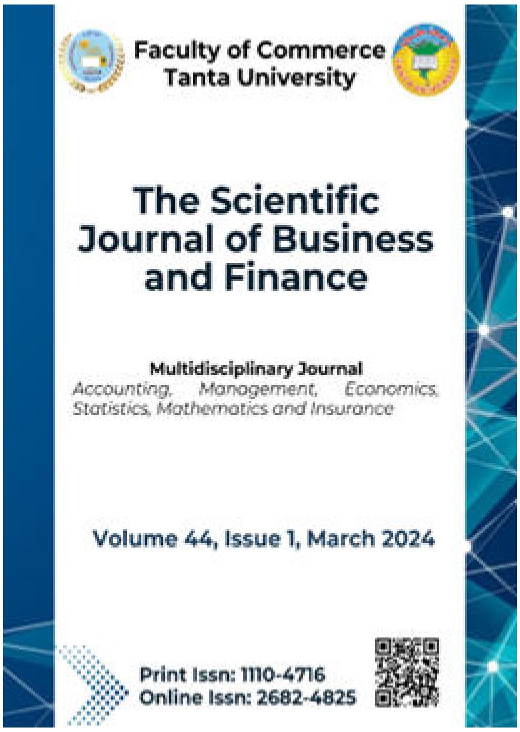

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E-Waste management: Economical, environmental and health concerns for developing and least-developed countries

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E-Waste management: Economical, environmental and health concerns for developing and least-developed countries

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Abstract

The paper aims to investigate electronic and electrical equipment waste management (EEEWM) or e-waste management. In this regard, the paper starts by focusing on the economic importance of e-waste management via reuse and recycling along with other benefits of recycling on preserving limited resources, eliminating environmental degradation, and negative impact on human health. Moreover, the paper covers the negative consequences of e-waste on the environment and health. Afterward, the paper investigates the e-waste dilemma in developing and least-developed countries in a sample of developing and least-developed countries. Then, the paper handles -e-waste management and how to achieve effective e-waste management.-- Finally, the study provides a set of recommendations and policy implications.

Keywords: E-waste management, Economic return, Recycling, Environmental degradation, Health.

1. Introduction

Indisputably, the accelerated progress in the quality of life, technological progress, and population growth, along with changes in consumers' behaviors and preferences along with patterns of consumption, have led to a scale-up in the demand for electrical and electronic equipment (EEE). Recent growing demand for EEE devices has also led to a notable increase in EEE waste or e-waste. Based on the "Global E-waste Statistics Partnership (GESP)" report, the global generated e-waste has increased by more than 21% in the last five years. For instance, around 57.4 million tons (Mt) of e-waste was generated in 2021. Only around 17.4% of generated e-waste is formally recycled, whereas the remaining end up either in landfills, incinerators, or exported to low-income countries (Forti et al., 2020).

The difference between e-waste and solid waste is that e-waste has dual attributes of hazardousness and resourcefulness (Ilankoon et al., 2018; Oswald & Reller, 2011). From a resource and economic utilization perspective, e-waste contains metal and non-metal components that are highly recyclable. E-waste also contains precious metals of which the grade is dozens or even hundreds of times higher than that of crude ores (Ashiq et al., 2019; Cui & Zhang, 2008). According to(Debnath et al., 2018), e-waste contains up to 60 different types of metals such as copper, silver, gold, palladium, aluminum, and iron. (Balde et al., 2017) state that the quantity and value estimated of metals waste materials in e-waste in 2017 are as follows: the reserves and value of iron/steel of 16,500 kiloton (kt) (9 billion Euros), copper of 1900 kt (10.6 billion Euros), aluminum of 220 kt (3.2 billion Euros), gold of 0.3 kt (10.4 billion Euros), silver of 1.0 kt (0.58 billion Euros), and plastics of 8600 kt (12.3 billion Euros). The recycling cost of metal from e-waste is far below the mining of crude ore (Chancerel et al., 2009; Vidyadhar, 2016), which means that e-waste recycling is an energy-saving and environmentally friendly approach (Anand et al., 2013; Khaliq et al., 2014; Thakur & Kumar, 2020). The total economic value of the recyclable resources contained in e-waste is as high as 57 billion USD, which is higher than the gross domestic product of most least-developed countries in the world (Forti et al., 2020).

On the contrary, e-waste has a variety of hazardous heavy metals that negatively influence the environment, human health, and wildlife, such as lead, mercury, and cadmium. Moreover, e-waste has persistent organics such as polychlorinated biphenyls and brominated flame retardants (He et al., 2017; Quan et al., 2014; Wu et al., 2015, 2016). The social cost of e-waste is represented by its impact on environmental degradation, human health, and wildlife. Unfortunately, the industrial infrastructure and recycling technology in developing and least-developed countries tend to be informal and primitive, in which workers adopt crude methods to separate what is needed from e-waste, which has a negative and irreversible impact on the local, regional, and even global ecological environment. Based on the considerable volume and rapid growth rate of e-waste, there must be an understanding of the influence and potential hazards of e-waste. A discussion of sustainable e-waste management and recycling technology is also required to form a comprehensive solution for e-waste (Awasthi et al., 2019). E-waste management in developing countries in general and in least-developed and African countries, in particular, has either little or no regulation in which e-waste is disposed of in open dumpsites, landfills, or incineration generating which causes pollution along with its impact on public health (Maes and Preston-Whyte, 2022). Moreover, developing and least-developed countries are considered the leading importers of used and refurbished EEE from developed and higher-income countries in vast amounts since EEE is cheaper relative to brand-new EEE.- Thus, the majority of imported used EEE are obsolete, irreparable and are thrown away with other municipal wastes to local dumpsites (Lebbie et al., 2021; Maphosa and Maphosa, 2020).

The transboundary shipments of hazardous e-waste from high-income countries to developing and least-developed countries have also deepened the problem of environmental degradation. Despite the majority of high-income nations having developed policies and advanced recycling techniques, they continue to export e-waste to low-income countries since the cost of disposal is still high relative to exporting it as e-waste. (Moeckel et al., 2020; Bimir, 2020).

Although efforts and attempts to mitigate the problem of e-waste in developing countries e-waste has remained a significant concern. Additionally, challenges in e-waste management in developing and low-income countries have intensified due to a lack of environmental regulations and a lack of funds. Many countries also need more knowledge, policies, guidelines, and proper disposal infrastructure, which results in the build-up of e-waste in uncontrolled dumpsites (Bimir, 2020; Schmidt, 2006). The relaxed e-waste legislation, along with illicit practices such as open incineration, acid leaching, and illegal dumping, is still being carried out by the informal sector in the majority of developing and least-developed countries (Murthy and Ramakrishna, 2022; Herat and Pariatamby, 2012; Nnorom and Osibanjo, 2008b). Finally, low levels of knowledge, education, and culture about the hazardous substances in waste and their negative impacts on health and the environment are still predominant in low-income countries (Forti et al., 2020).

Given the scale of environmental pollution and public health threats resulting from informal recycling. This study examines e-waste management, informal e-waste recycling, environmental degradation, and health impacts in developing and least-developed countries. This study proposed a question about what is the extent of environmental pollution and health consequences due to e-waste dumping and informal recycling practices in developing and least-developed countries?

The study problem emerges from the fact that developing and least-developed countries suffer from improper e-waste disposal, informal recycling practices, illegal transboundary shipment of e-waste, the lack of collaboration between governments and international organizations in reducing the impact of e-waste pollution, along with ineffective laws and regulations of e-waste management. Thus, the study focuses on environmental pollution and public health impacts resulting from e-waste dumping and informal recycling practices. The study also considers the economic benefits of recycling. Moreover, the study highlights the value of proper e-waste management on the economy, environment, and health in developing and least-developed countries to get rid of the illegal diversion of e-waste to dumpsites and landfills and to create value and opportunities. Additionally, the study aims to provide proposals and policy implications to eliminate negative consequences that arise from improper e-waste disposal on health and the environment and to maximize economic benefits from recycling and e-waste management.

Figure 1a shows annual world-generated e-waste from 2014 to 2019. Although the e-waste growth rate declined from year to year, the e-waste generated in 2019 was 21% higher than the e-waste generated in 2014.

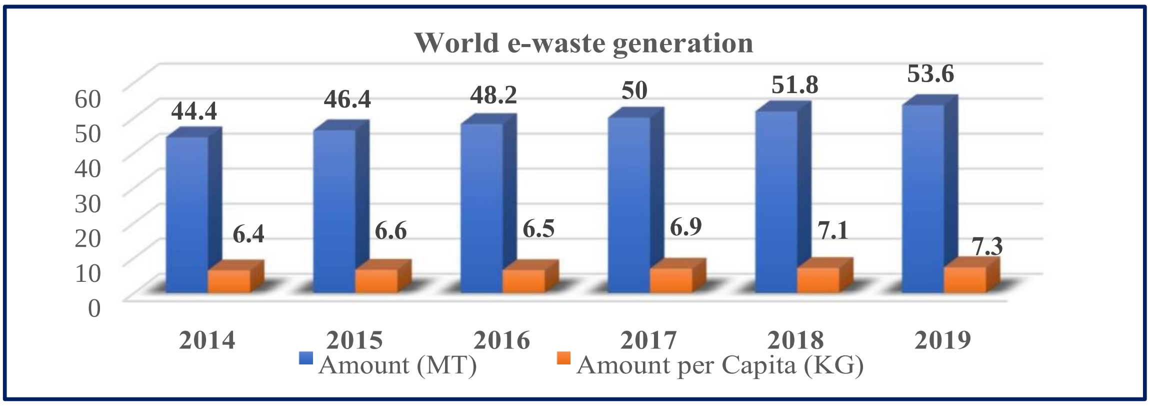

Figure 1. a Worldwide e-waste generation (MT) and per capita e-waste generation (KG)

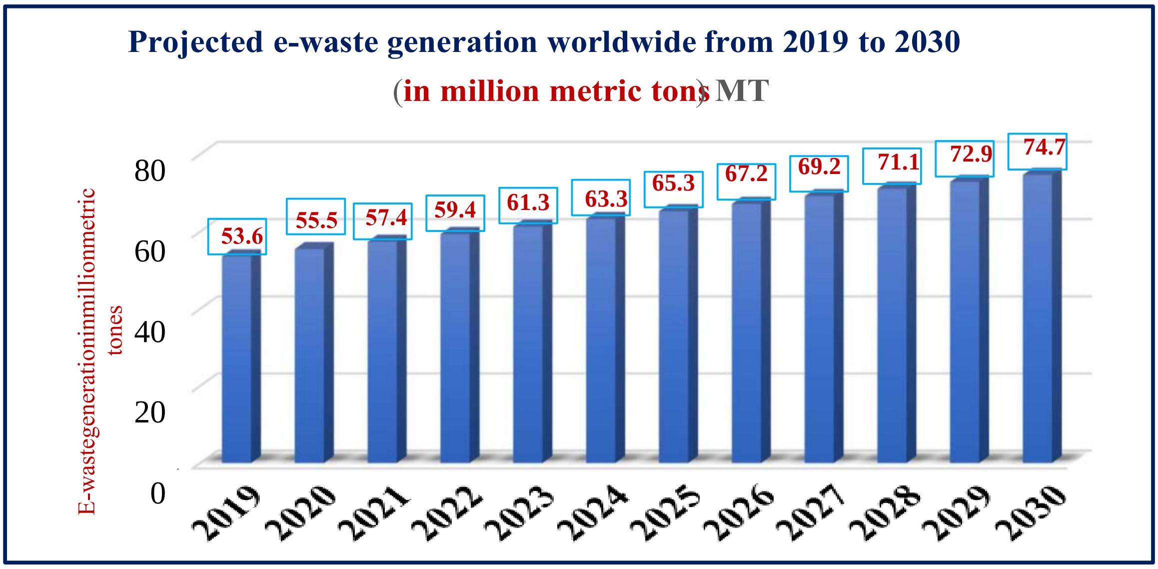

Figure 1. b projected e-waste generation worldwide from 2019 to 2030

However, projected e-waste generated in 2030 will increase by 39% relative to e-waste generated in 2019, as seen in Figure 1. b

Figure1.c exhibits the worldwide e-waste generated in 2019 per continent and per capita. The figure shows that the highest e-waste generated per continent is from Asia, whereas the lowest

e-waste generated is from Africa. However, the highest e-waste generated per capita is from Europe, while the lowest e-waste generated is from Oceania.

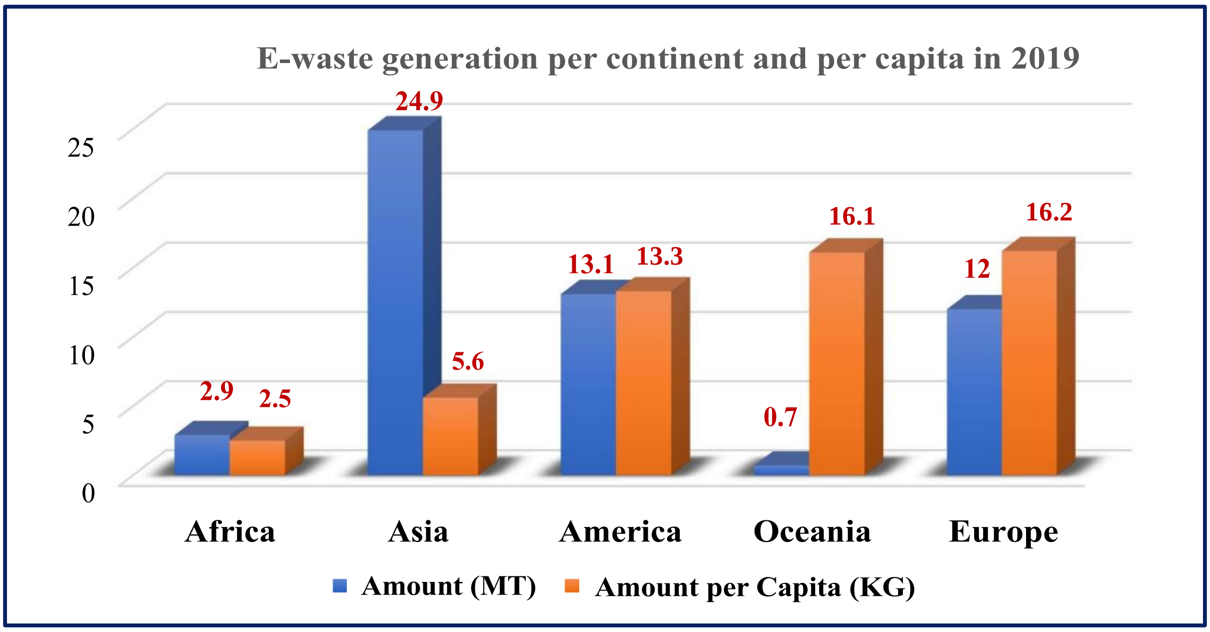

Figure 1. c E-waste generated per continent and per capita 2019.

Figure 1.d provides e-waste generated from different sorts, while Figure 1. e provides the ratio of formal recycled e-waste relative to e-waste generated. From Figure 1.d, it is realized that the highest e-waste generated is from small equipment, 32.5%, followed by large equipment, 24.4%, followed by temperature control equipment, followed by screen and display monitoring, 12.5%, then small electronic communication equipment, and 1.7% from electric light. Figure 1. e shows that formal e-waste recycled represents only 17.4% of total worldwide e-waste generated in 2019, whereas about 82.6% represents non-formal recycling.

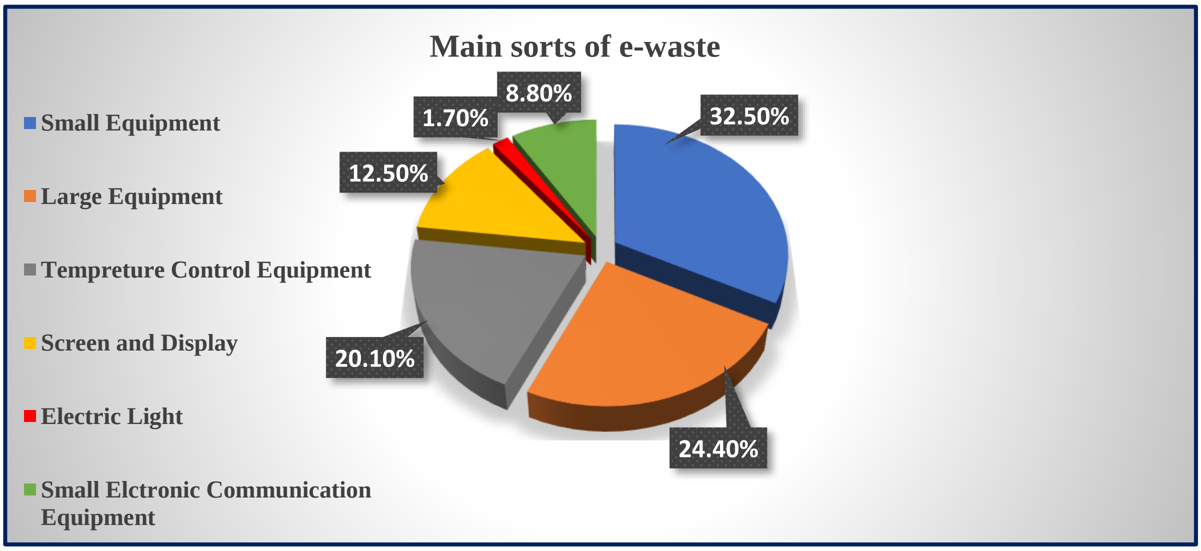

Figure 1 d. Different categories of e-waste

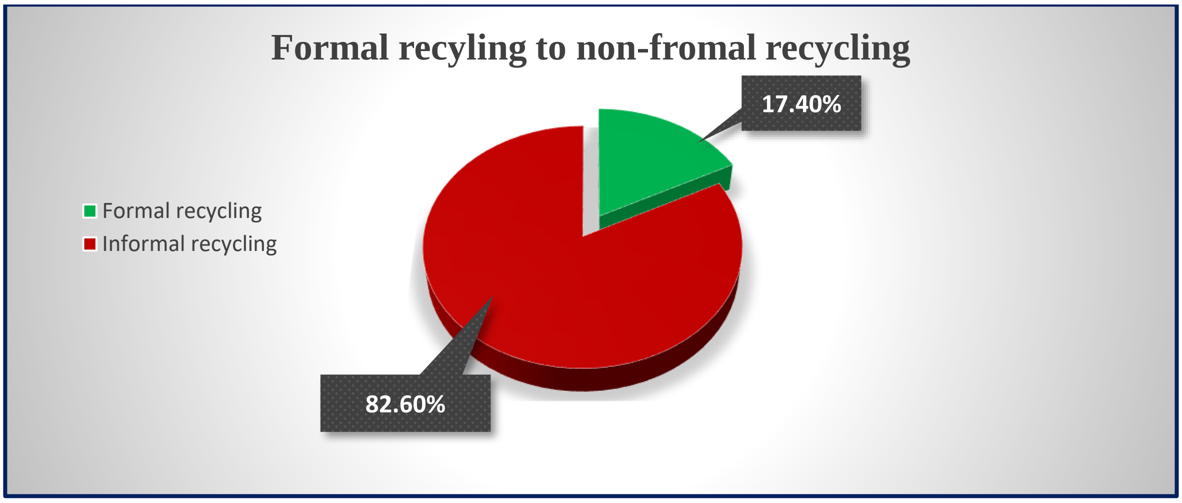

Figure 1. e formal recycling e-waste relative to non-formal e-waste recycling

Sources of figures are based on (Forti et al., 2020) data

The study is organized as follows: section 2 displays existing literature related to e-waste generation and management. Section 3 deals with e-waste components and economic return. Section 4 presents the impact of e-waste on health and the environment. Section 5 handles the e-waste dilemma in developing and least-developed countries. Section 7 provides recommendations. Finally, section 8 presents the conclusions.

2. Literature Review

As a result of conducting extensive research on the effects of e-waste, it has been discovered that the literature can be categorized into two main groups. The first group comprises studies that comprehensively examine the impact of e-waste on the economy, health, and environment. This group of studies provides a holistic understanding of the effects of e-waste on the world. The second group focuses solely on the impact of e-waste on health and the environment. This group of studies delves deeper into the specific impacts of e-waste on human health and the environment.

2.1 Studies related to the impact of e-waste on the economy, health, and the environment

Osibanjo and Nnorom (2007) investigate the challenge of e-waste in developing countries. They stress the role of information and telecommunications technology (ICT) and computer internet networking in human life, even in developing countries. They stress that rapid growth in ICT has led to an improvement in the capacity of computers but simultaneously to a decrease in the product's lifetime, as a result of which increasingly large quantities of e-waste are generated annually. ICT development in most developing countries depends more on secondhand or refurbished EEEs, most of which are imported without confirmatory testing for functionality. Thus, large quantities of e-waste are presently being managed in these countries. They also pay attention to challenges facing developing countries in e-waste management, such as the absence of infrastructure for waste management, the need for legislation dealing with e-waste, and the absence of any framework for end-of-life (EoL) product take-back. The study mainly focuses on these issues in Nigeria as a case study of developing countries. The study stresses the role of effective management of e-waste in developing countries via the establishment of product reuse via remanufacturing and efficient recycling facilities. (Dias et al., 2017) investigate a systematic analysis of EEE processing procedures for 134 recycling companies in Brazil by contacting them and confirming the activity. It is found that in spite of the recent implementation of national waste management policies, federal and local governments still need to have control over the number of active EEE recycling companies in the country. It is possible to explain the role of the different agents in the Brazilian recycling scenario in which the study shows that 89% of the Brazilian recycling companies undertake the pretreatment phase in the recycling process - sorting and dismantling - and that at least 92% dismantle EEE manually. Finally, it is shown that EEE is more complex to recycle, and they are still being shipped abroad for foreign downstream companies and the generated revenue by the EEE recycling market can financially support up to five agents involved in the EEE flow.

(Dias et al., 2018) discuss the management of e-waste using the Australian recycling scheme as an example. The investigation of the actual recycling process and the associated cost analysis reveal essential outcomes for the decision-making process of determining which equipment (or materials) will be exported and which will be recycled domestically. It is shown that scrap computers are the only equipment with enough intrinsic value to justify domestic recycling without requiring any external subsidy. Furthermore, the importance of such subsidies, regulations, and monitoring are discussed, principally for e-waste with an intrinsic value smaller than computers. Results show that labor denotes more than 90% of the cost of first stage recycling in Australia as a higher wages countries. In the way of achieving better waste management worldwide, the study provides arguments to encourage better monitoring of recycling processes undertaken internationally and the promotion of downstream recycling processes in developed countries.

(Abdallah et al., 2018) investigate the feasibility of waste-to-energy technologies (WTE) strategies in middle-income developing countries of the Middle East and North Africa (MENA) region. Multiple waste management scenarios involving incineration and anaerobic digestion are evaluated based on energy, economic, and environmental parameters. A multi-criteria assessment is conducted for Kafr El-Sheikh governorate (Egypt) with socio-economic and demographic features as a sample of MENA countries. The actual waste generation rates and characteristics of Kafr El-Sheikh are measured through a comprehensive field study. It is found that anaerobic digestion with recycling is the optimum strategy for Kafr El-Sheikh, with an annual energy potential of 1170-kWh per ton of waste and net economic savings of 6.5 million USD. This optimum waste management scenario is extended to selected MENA countries to investigate the potential benefits of shifting to WTE-based waste management strategies. The total annual energy production is estimated to be 103,000 GW/h, which translates to 17% of the total energy consumption. Moreover, greenhouse gas emissions are reduced by around 98,500-Gg CO_2 annually, which is around 6.5% of the total annual CO_2 footprint generated by the selected countries. Furthermore, the overall economic benefits range between −12 and 200 million USD for selected countries.

(Gollakota et al., 2020) provide the risks of e-waste on health and the environment. They also provide economic benefits from recycling along with metals and non-metal emerged from e-waste. Besides the technical standpoints in terms of upgrading the existing technologies, new approaches to e-waste management were elucidated in detail. The study also provides the drawbacks of e-waste management in developing countries relative to developed countries. Finally, the paper provides proposals, policies, and solutions to overcome legislative, environmental, and health problems emerging from e-waste in developing nations.

Garg (2020) explores the critical strategies to recover resources along with the processing and treatment of toxic and hazardous components of e-waste mitigation and management, which is an immediate and existing challenge for India. A combined framework based on the Grey concept and the DEMATEL technique has been proposed to determine the interdependence among the e-waste mitigation strategies (MS) by cause/effect analysis. The study reveals that ‘top management initiation and commitment towards return management’ is the most imperative and driving strategy in e-waste management and control. It also influences the other existing strategies. The study has also highlighted that e-waste mitigation can be effective if it concentrates on the effective implementation of e-waste policy, directives, and regulations such as extended producer responsibility(EPR), advance recycling fee (ARF), etc., technological and green innovations in recycling networks and strategic alliance among supply chain partners and e-waste recyclers. The cause-effect relationships are helpful to managers, Government agencies, and policymakers in learning crucial causal strategies that require imperative stress in dealing with e-waste issues.

(Mairizal et al., 2021) provides an estimation and projection of e-waste generation in Indonesia, as well as its potential recoverable metals’ value from 1996 to 2040, to address this gap. An advanced multivariate Input-Output Analysis (IOA) of the sales-stock-lifespan model and a dynamic, time-variant lifespan of products through the Weibull distribution function was used to provide a more accurate and extended estimation of e-waste generation in Indonesia. Results show that Indonesia's e-waste generation is projected to increase from approximately 2.0 (in 2021) to 3.2 million tons (in 2040), which corresponds to 7.3 (in 2021) to 10 kg/capita (in 2040). These represent economic values from 2.2 billion USD to 14 billion USD of Copper, Gold, Silver, Platinum, and Palladium in the e-waste. The study also maps the distribution of e-waste generation in Indonesia in which Java Island contributes up to 56% of the total e-waste generation in the country in 2021. The study also proposes a recycling system framework that includes possible processing routes and scenarios that integrate mobile/sub-station recycling facilities into existing extensive metallurgical facilities in the context of Indonesia.

(Panchal et al., 2021) estimate the e-waste generation in India using the market supply method combined with substance flow analysis to quantify the ordinary, precious, and critical raw materials embedded in EEE and further determine their recovery economic potential. Moreover, it discusses the impact of EEE recycling on the import of familiar, precious, and critical raw materials. The study considers the case of EEE management in India to determine its recovery economic potential. The analysis reveals that the recycling of EEE can fulfill the demand for a Platinum group of metals in the electronics industry. The maximum amount of critical raw materials has been found in television sets. EEE recycling can reduce dependency on importing critical raw materials such as antimony from other countries.

(Kumar et al., 2021) provide statistics about the e-waste problem that faces India. India has a massive generation of ‘‘electronic waste” with the unavailability of effective and efficient methods to dispose of it. Alterations in the lifestyle of the Indian population have contributed immensely to generating close to 3 million tons of e-waste. The problem rise from the fact that India recycles only less than 2 percent of its annual generated e-waste as against the global figure of 20 percent. Further, provided its hazardous effect on human health and the environment in the absence of sufficient and efficient management, along with the prospects and huge potential to produce recycled metals such as iron and steel, plastic, and other nonmetals, it needs to have appropriate policies and strategies in place followed by strict implementation. India's commitment to attain the SDGs 2030 (goals 3, 6, 8, 11, 12 and 14) will partially depend on how well India manages its e-waste in the future.

(Shahab uddin et al., 2022) review recent developments, challenges, and the prospect of e-waste. Various aspects of e-waste, including collection, pretreatment, and recycling, are also discussed. It is found that Europe is the leading collector of e-waste, followed by Asia, America, Oceania, and Africa. The monetary worth of e-waste raw materials is estimated to be \$57.0 billion. However, only \$10.0 billion worth of e-waste is recycled and recovered sustainably, offsetting 15.0 million tons (Mt) of CO_2. The significant challenges of e-waste treatment include collection, sorting, and inhomogeneity of waste, low energy density, prevention of further waste and emission, and cost-effective recycling. Only 78 countries in the world have e-waste-related legislation. Such legislation needs to be more effectively implemented in most regions. Developing countries such as south-eastern Asia and Northern Africa have limited or no e-waste legislation. Therefore, country-specific standards and legislation, public awareness, practical implementation, and government incentives for developing cost-effective technologies are sought to manage e-waste, which will play an essential role in the circular economy.

(Moossa et al., 2022) present a review of the reported works in the field of e-waste in the MENA region. The paper aims to shed light on various aspects of e-waste in the MENA region. The study covers various methods of estimating the quantities of e-waste, how it is presently managed in the MENA, the impacts of e-waste, and the regulations compliant with MENA are covered in the review.

Recently, the e-waste stream has begun to attract attention in certain countries of the MENA. The prime component of e-waste is mobile phones, which have penetrated very deeply into all regions of the world. The health hazards caused by e-waste stem primarily from heavy metals and halogenated plastics. The review finds that the health impacts caused by informal e-waste handling in MENA countries should be given more attention and should be covered in the literature. Regarding the regulations on e-waste disposal, countries need to implement these regulations to control e-waste penetration effectively.

Sekyere and Aladago (2023) employ Material Flow Analysis (MFA) to investigate five critical informal e-waste recycling processes and risk analysis to evaluate environmental, economic, and health safety. The risk assessment shows that there are significant risks to environmental, economic, and health safety for all processes. When considering the overall risk assessment across all categories of e-waste components. The key findings of the study focus on the assessment of the so far not known informal e-waste process workflows, the identification of emerging fractions, the remains of potentially hazardous fractions, and the identification of the primary economic drivers in informal e-waste dismantling. Recommended action areas involve the incorporation of the informal sector, guided by the insights derived from the MFA and risk assessment.

(Paes et al., 2023) aim to identify the main enablers of innovations in municipal solid waste management (MSWM). Four municipalities in Brazil were selected because they presented highly innovative actions in the MSWM that reduced trade-offs between circular economy (CE) and climate change (CC). Based on an analysis of the economic, environmental, and operational performance of the four MSWM, they find reductions in Greenhouse Gases (GHG - CO_2eq per inhabitant) of up to 90% and lower waste management costs per inhabitant compared to the national average. Four main enablers make the innovations possible to accelerate the transitions to a more circular and low-carbon economy in municipalities: local capacity, intergovernmental collaboration, MSWM with local partners, and environmental education that promotes social participation. The study contributes to developing a method to identify enablers at various system levels and propose technological approaches and practices that enable innovation in MSWM. Such measures can serve as a subsidy for circular disruption and as a basis for intervention in MSWM, especially in developing countries.

2.2 Studies related to the impact of e-waste on health and the environment

Nagajothi and Felix Kala (2015) examine the current scenario of e-waste generation, data on components and hazardous substances of e-waste that are creating environmental pollution, and human exposure to these chemicals, resulting in adverse effects based on recycling, incineration, and landfill disposal of e-waste. The current practices of e-waste management in India suffer a number of drawbacks like inadequate legislation, health hazards due to informal recycling, poor awareness, and reluctance on the part of the corporate to address the critical issues. The impacts are intense when toxic materials enter the waste stream with no special precautions, creating contrary effects on the environment and human health, and when economically valuable materials are dumped, resources are wasted, or unhealthy conditions are developed during informal recycling. They propose detailed assessments for current and future scenarios, including quantification, classification, existing disposal practices, environmental impacts, and occupational health hazards. E-waste collection, transportation, treatment, storage, recovery, and disposal need to be established at national and regional levels for the environmentally sound management of e-waste.

Ikhlayel (2017) introduces a systematic approach to e-waste management; a process termed integrated e-waste management (IEWM) is a theoretically feasible technique in which municipal solid waste and e-waste management systems are managed. Integrated e-waste management represents an advance in the controlled disposal of e-waste and improvements in local environments and public health in developing countries. The study employs a systematic approach that combines field trip work, systematic literature review, and quantitative data analysis to propose a solution that can bring benefits in the short and long term. The study proposes that an integrated approach can improve e-waste handling in developing countries by addressing region-specific issues simultaneously.

(Asante et al. 2019) address obstacles and drawbacks that face e-waste management in Africa, such as inadequate infrastructure for e-waste management and nonenforcement of laws. Multitudes of hazardous substances are released due to the crude way e-waste is recycled and could pose risks to humans and the environment. However, the paper provides opportunities overflow if it is handled well, such as precious metal recovery for industry, employment opportunities and economic benefits to e-waste collectors, helping to clean the environment, refurbishment for sale of cheap electronic and electrical equipment, benefits of recovered metals over mineral mining, among others.

Ahirwar and Tripathi (2020) address the emerging risks of the employed techniques in recycling that have an impact on health and the environment. E-waste can be a source of toxic substances such as heavy metals and persistent organic pollutants, including polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), brominated flame retardants (BFRs), and other hazardous substances. To efficiently exploit the benefits of e-waste recycling without threatening public health, a holistic approach encompassing improved product design and recycling rate and minimal emission of hazardous e-waste pollutants to the environment is required. Thus, the paper discusses the opportunities, constraints, and strategies for improved e-waste management. Furthermore, the study highlights the recent global trend in e-waste generation. It provides an overview of the e-waste recycling process and the impact of e-waste pollutants on health. Finally, some proposals to make e-waste recycling an efficient and safer process have been discussed.

(Rautela et al., 2021) focus on challenges in managing e-waste arising from a lack of technical skills, poor infrastructure, inadequate financial support, and inactive community engagement. The study provides a systematic review of efforts to overcome these challenges in the context of improper recycling protocols of e-waste and their toxic effects on human health and the environment. An inventory of end-of-life electronic products, which can be established through the creation of an environment-friendly regulatory regime for recycling, is essential for the proper control of e-waste. An approach has been articulated to help implement effective e-waste management in both developed and developing countries.

Maes and Preston-Whyte (2022) run a survey about e-waste in Africa. They calculate the total e-waste in Africa (locally produced plus imported e-waste) for 2019 to be between 5.8 and 3.4 metric tons. This is believed to be an underestimate; significant data gaps exist, hindering more precise estimates. The data is further complicated by, sometimes intentional, differences in labeling and reporting between formal and intermittent informal importers. Based on available data, the leading African recipients of e-waste are Nigeria, Ghana, Tanzania, Kenya, Senegal, and Egypt as countries of concern. The lack of proper waste management in developing countries leads to environmental contamination and human exposure. They propose a managed regional and global approach to tackle e-waste. Moreover, regulatory frameworks, together with monitoring and compliance mechanisms, need to be developed, financed, and enforced.

(Frazzoli, et al. 2022) present public health strategies to assess and manage the risk of e-waste using the one-health approach. The benefits and challenges of integrated biomonitoring are described, along with ad hoc biomarkers of exposure, effect, and susceptibility, with a particular focus on metals and metalloids. The integration and coordination of human and animal biomonitoring will benefit the safe and sustainable management of novel technologies.

(Liu et al. 2023) provide a systematic overview of the status quo of e-waste recycling globally. E-waste is placed into a framework, grouped by product type, quantity, composition, environmental health risk, and global impact. Management measures, legislative policies, current disposal, and transboundary movement are summarized at international, regional, and national levels, illustrating the status and challenges of e-waste collection and disposal. Techniques such as physical dismantling, component recycling, metal extraction, and reutilization of nonmetallic materials are described, as they have long-term impacts on the ecosystem. The study provides a global solution for the recycling of e-waste.

(Andeobu et al. 2023) examine informal e-waste recycling, environmental pollution, and the extent of environmental and health impacts in selected African countries. The study focuses on environmental pollution and public-health impacts arising from e-waste dumping, informal recycling practices, illegal transboundary shipment of e-waste to the selected countries, and the interventions of governments and international organizations in reducing the impact of e-waste pollution and informal recycling practices in Africa. Findings document that individuals working within e-waste sites and residents in nearby communities are exposed to a number of toxic substances, some at potentially concerning levels.

(Jain et al. 2023) present a set of various sources of e-waste, environmental hazards, composition and characterization, and e-waste scenarios in India and the global world. For the sake of the future, techniques of handling and processing, as well as e-waste recycling, should be used. The paper mainly outlines the issue of e-waste along with covering the improvement and plan to tackle the issue.

(Jabbour et al. 2023) investigate criteria that influence user behavior regarding e-waste recycling, using seven criteria (intention to recycle e-waste, awareness of e-waste recycling, environmental concern, attitudes towards e-waste recycling, subjective norms, perceived behavioral control, and WTP for e-waste recycling). A questionnaire, interviews, and several analytical techniques are used to identify the most relevant criteria for e-waste recycling. Willingness to pay (WTP) is used as a reference criterion; the remaining six criteria are investigated as variables, with the aim of uncovering the relations among them and determining which had the most significant impact on WTP. Results revealed that individuals with pro-social solid attitudes are more aware of the need to recycle e-waste. Moreover, those who dispose of waste correctly in specialized centers are more aware of the need to recycle. The study highlights the importance of raising awareness at the group level to promote e-waste disposal as a social norm.

From the preceding literature, it is notable that e-waste has a crucial influence not only on health and the environment but also on the efficient utilization of economic resources.

3. E-waste components and economic return

E-waste has very complex components, and it mainly includes substances such as steel, iron, non-metals, glass, polymer plastics, wood, plywood, printed circuit boards, concrete, ceramics, rubber, etc. (Betts, 2008). Figure 2 provides a detailed classification of different sorts of e-waste.

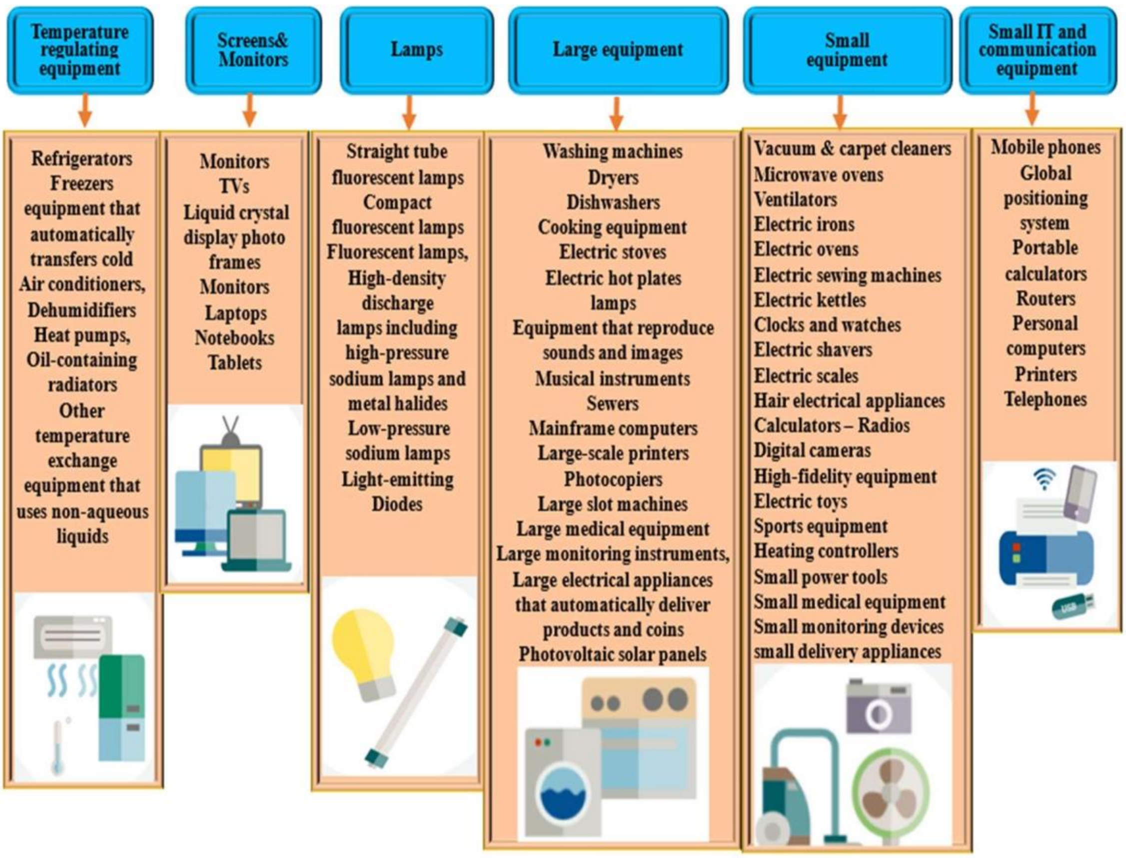

Figure 2: description of different categories of e-waste

More than 61 components could be obtained from different sorts of e-waste. Substances can be classified into common metals, precious metals, glass, fiber, concrete, plastic/ biomass, added elements, rear elements, and rear earth elements. Figure 3 shows the main substances that can be obtained from e-waste.

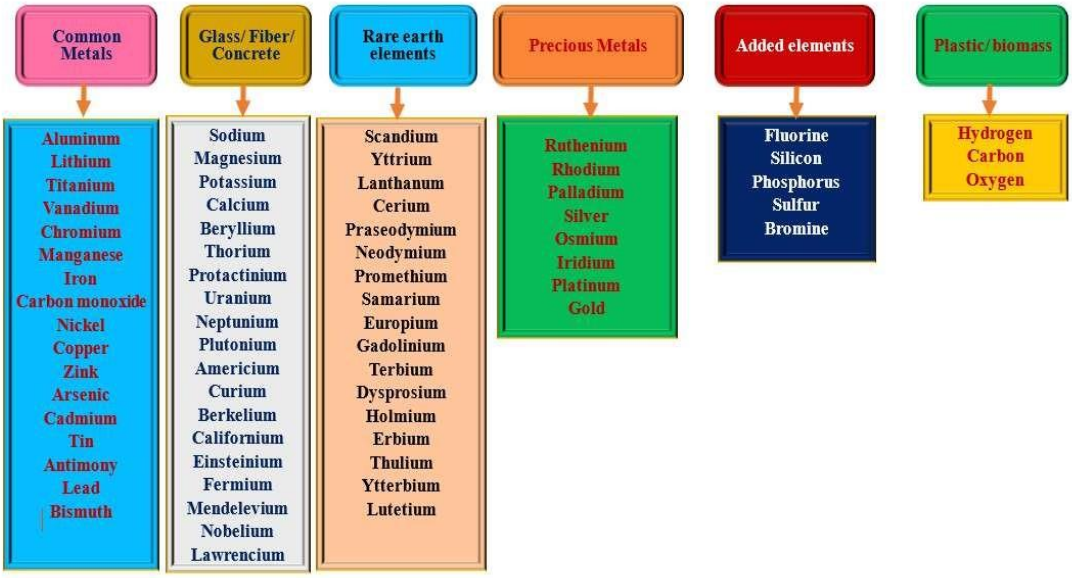

Figure 3: metal and non-metal elements emerged from e-waste

For instance, iron and steel represent nearly 47% of e-waste, plastics about 21%, copper around 7 %, and glass about 5 %, along with other components (Zeng et al., 2018).

For instance, one ton of e-waste printed circuit boards can provide 143 kg of copper, 0.5 kg of gold, 40.8 kg of iron, 29.5 kg of lead, 2.0 kg of tin, 18.1 kg of nickel, 10.0 kg of antimony (Kolias et al., 2014). Non-metallic materials such as engineering plastics and glass fibers are also of considerable value through secondary use (Rajagopal et al., 2017; Sahajwalla & Gaikwad, 2018). In general, the dominant polymers in EEE were found to be polystyrene, acrylonitrile-butadiene-styrene, blends of polycarbonate, high-impact polystyrene, and polypropylene (Ma et al., 2016). The glass fiber is mainly composed of metal oxides, such as alumina, potassium oxide, sodium oxide, and calcium oxide., etc., which are generally present in the resin laminate of the circuit board (Khan et al., 2022).

From the preceding considerations, recycling of e-waste is required for many reasons: to eliminate environmental degradation, to protect health, to manage existing natural resources efficiently, and for economic considerations. Therefore, there is an urgent need to reuse and recycle e-waste for the following reasons;

- The cost of recycling matter is less than extracting raw material.
- Recycling a product needs less or no energy, whereas raw material needs different sorts of energy to extract the matter (iron, copper, etc.)

- Different sorts of pollutants emerged from the industrial extraction process, while the extraction process for mining and industrial activities causes environmental degradation along with their impact on health.
- Recycling is less polluted relative to raw materials extraction.
- Minimizing social costs arising from mining and polluted activities increases health budgets and environmental protection programs.
- To preserve limited and scarce resources for the next generations.

4. The impact of e-waste on health and the environment

Although economic benefits emerged from e-waste recycling, as mentioned earlier, harmful consequences emerged, which have negative impacts on human health and the environment. Improper e-waste management has led to hazardous wastes that influence human life. Therefore, this section deals with the impact of e-waste on human health and the environment.

4.1 The influence of e-waste on human health

Inappropriate, unsafe, and informal e-waste disposal leads to different sorts of pollutants. Many diseases are related to hazardous e-waste components, as displayed in Figure 4. Figure 4 displays 14 major hazardous components released from e-waste.

Figure 4: Major hazardous and chemical elements emerged from e-waste

These components negatively affect human health in which these heavy metals and substances;

- Accumulate in Kidney
- Cause neural damage

- Disrupt endocrine system functions
- Damage to the nervous system, blood system & kidney damage.
- Affect brain development of children
- Chronic damage to the brain
- Respiratory and skin disorders
- Carcinogenic(lung cancer)
- Skin diseases such as warts
- Different sorts of allergy
- Different sorts of cancer
- Immune system damage

4.2 The influence of e-waste on the environment

Irresponsible and informal e-waste management leads to different pollution, such as air pollution and soil and water contamination.

4.2.1 E-waste harmful influences on air

Informal e-waste disposal by dismantling, shredding, or melting the components increases dust particles and chemical emissions such as dioxins, CO_2, SO_2, and other toxic gases. The consequences of air pollution cause respiratory system diseases, other sorts of allergies, chronic diseases, and cancers. Air pollution also affects wildlife. Developing and least-developed countries are mainly suffering from the problem of informal e-waste management and weak and ineffective rules and regulations, which have increased levels of air pollution in recent years. People who deal with e-waste disposal or live near informal disposal areas are mainly vulnerable to air pollution. Thus, the problem of air pollution kept on increasing day-by-day. Over time, the quality of air, water, and soil gets polluted, resulting in environmental degradation.

4.2.2 E-waste toxic influences on soil

Informal and improper disposal of hazardous e-waste in open, non-sanitary landfills spreads heavy metals into the soil, which leaches directly into crops. These toxic crops directly affect wildlife and human health. Moreover, heavy metals cause a deterioration in farming productivity.

4.2.3 E-waste toxic influences on groundwater

Subsequent soil contamination, heavy metals released from e-waste, such as mercury, lithium, lead, and barium, leach more plunging into the earth to reach groundwater. After heavy metals pass through groundwater, they reach rivers, ponds, and lakes, which toxin water. This toxin water is detrimental to animals, plants, and communities. From prior sections, there is an urgent need to maximize the economic benefits that emerge from e-waste along with eliminating negative consequences on health and the environment via e-waste management. The following section will focus on e-waste in developing and least-developed countries.

5. **E-waste dilemma in developing and least-developed countries**

Developing and least-developed countries generate about 52% of the worldwide e-waste generation, whereas formal e-waste recycling is about 10% (Forti et al., 2020). (Alam & Bahauddin, 2015) state that 80% of e-waste generated in developed countries is sent for recycling and disposal in African and Asian countries. The domestic and overseas load of e-waste is challenging to handle for a developing country. Unfortunately, e-waste collection in developing and least-developed countries is primarily informal and unauthorized. Only 20% of total e-waste is recycled without adequate occupational safety precautions (Ahirwar& Tripathi, 2021).

In a nutshell, the main challenging issues of e-waste management in developing countries are:

1. The quantity of e-waste generated is a primary concern since there is a lack of infrastructure to manage e-waste properly. Moreover, the significant dependence on EEE is on secondhand EEE, which is a pressing issue as it has poor quality and hazardous content.
2. The inventory assessment of e-waste in the majority of developing and least-developed countries needs improvement or does not exist.
3. The transboundary of e-waste from developed to developing and least-developed countries for recycling leads to a situation in which EEE products become e-waste in developing countries, which worsens e-waste management in those countries
4. The need for knowledge regarding the toxicity of e-waste.
5. E-waste components are often mixed with municipal solid waste, and both are treated inappropriately.
6. Lack of knowledge about the negative consequences of current e-waste treatment practices on human health and the environment.
7. Legislations to regulate and control the import and disposal of generated e-waste do not exist, are poor, or are inactive in the majority of developing and least-developed countries. Undoubtedly, active legislation can diminish the hazardous nature of e-waste management in those countries.

5.1 Bangladesh, Egypt, Ghana, India, Nigeria, and South Africa as case studies for developing and least-developed countries.

This section explores the ways of how Bangladesh, Egypt, India, and Nigeria, deal with e-waste.

5.1.1Bangladesh

Bangladesh generates 3 million MT of e-waste each year, and based on the' Digital Bangladesh' project, it is expected to witness an increase in the consumption of e-products (Mahmud et al., 2020; Aziz, 2020). Bangladesh amended the first draft of 'e-waste management rules' in 2011 and updated it again in 2021 to include hazardous waste management rules. However, the implementation of the legislation is not efficiently maintained, which hinders the proper establishment of the e-waste management process in Bangladesh.

Only 3% of the total e-waste generated is formally recycled, whereas the informal sector controls the recycling process in Bangladesh. Thus, unrecycled e-waste ends up in different landfills, water drains, and channels, polluting the environment (Yousuf & Reza, 2011). In Dhaka, 475 tons/day of inorganic e-waste is recycled, only 15% of total e-waste generation/day. The unrecycled waste contaminates the environment owing to inadequate disposal techniques (Khuda, 2021). Random dumping of e-waste involves hazardous metals such as lead, mercury, chromium, and cadmium, which causes severe health and environmental hazards in Bangladesh.

The problem of informal e-waste is that the staff needs to be more skilled and aware of the hazards of handling e-waste. In these workplaces, chemical risk analysis, task risk analysis, or health risk analysis should be appropriately assessed. The primary victims of e-waste exposure are children and women. The environment and Social Development Organization (ESDO) study states that more than 83% of children workers involved in e-waste management in Bangladesh are exposed to hazardous and toxic substances in e-waste (ESDO, 2012). Fifty thousand children are engaged in Bangladesh's unauthorized e-waste collection and recycling process. Besides, children may be exposed to e-waste-derived chemicals and waste from landfill sites in their everyday lives due to the unhealthy recycling practices of Bangladesh. However, the government has imposed several restrictions to maintain proper e-waste recycling, as e-waste recycling in a systematic way can be a profitable beneficial business model in developing and least-developed countries like Bangladesh (Garlapati, 2016), and Bangladesh still has the opportunity to transform e-waste into a resource.

5.1.2 Egypt

Egypt is considered the highest generator of e-waste in Africa and a significant destination for e-waste importation from high-income countries (Sakr et al., 2021). In 2019, the country generated 586,000 tons of e-waste, and it is expected to increase to 5.7% by the end of 2022 (Forti et al., 2020). E-waste in Egypt is generated through local consumption of new EEE and through illicit imports of used EEE to cope with the high domestic demand for cheap secondhand products (Sakr et al., 2021).

Currently, there needs to be an effective national legislation or financing mechanism that deals with e-waste. E-waste management activities are dominated by informal collectors and recyclers (Marzook et al., 2021). It is estimated that around 10% of e-waste generated is formally recycled, and the rest is directly moved to open landfills, leading to enormous environmental pollution and health concerns (Sakr et al., 2021). Although the volumes of e-waste generated are massive, formal recycling activities are limited and primarily operate on a small scale (Ibanescu et al., 2018; Isernia et al., 2019).

The management of e-waste in Egypt is controlled by informal recyclers, who buy and collect old EEE from consumers through street dealers (Sakr et al., 2021). The imported second-hand EEE are sold to unregistered second-hand electronic workshops, mainly located in densely populated areas of Cairo. These unregistered e-waste dealers refurbish, repair, and resell them locally as second-hand devices or use them as replacement parts to fix other devices. The unwanted parts are often dumped in landfills or sold to informal recyclers depending on the value ascribed to the item (Marzook et al., 2021). Even though the environmental law was approved in 1994, e-waste management regulation needs to be more effectively enforced (Sakr et al., 2021). In 2007, the law was amended to include a segment that addresses the management of hazardous waste under which e-waste is classified. The environmental law bans the import of hazardous waste. The Egyptian environmental law is similar to the EU regulations and requires environmental impact assessment for any activity carried out; it keeps a record of its risk assessment, impact on the environment, training of waste handlers, transportation of waste, and health and safety standards.

Egyptian Environmental Affairs Agency (EEAA) is a regulatory body that sets environmental plans and supervises any violations of environmental law, including mismanagement of all types of waste, including e-waste (Tarek & El-Haggar, 2019).

5.1.3 Ghana

In recent years, vast quantities of e-waste imports from Europe and the USA have accessed Ghanaian markets. In 2017, Ghana imported around 215,000 kilotons of EEE from Europe and the USA. 60% of the imported amount is used as EEE with a shorter life span, and the remaining 40% is scrapped to be disposed of (Holt ̈ et al., 2017; Daum et al., 2017). Consequently, Ghana is known as a popular e-waste dumping destination and informal recycling, especially at the Agbogbloshie dumpsite in Accra. Agbogbloshie is a significant center for informal e-waste recycling and disposal in Africa, where substantial manual dismantling of e-waste parts is conducted (Bimir, 2020; Caravanos et al., 2011). This informal recycling in Ghana is commonly done by low-income residents of women and children as a significant source of livelihood (Bimir, 2020; Martin, 2012; Caravanos et al., 2011).

The 2016 E-Waste Control and Management Act regulates the management and disposal of hazardous waste, e-waste, and related products. It includes a schedule that designates the categories of e-waste to be controlled, as well as a list of e-waste with specific elements such as arsenic, zinc, cadmium, chromium, etc. The act notably prohibits the transportation, sale, purchase, as well as import and export of hazardous wastes or other waste as classified in the schedule; it also provides definitions on what used EEE is and specifies the establishment of an electrical and electronic waste management fund (EEWMF). The main objective of EEWMF is to finance the management of e-waste and reduce the negative impact of e-waste on human health and the environment.

Even though Ghana has numerous legislations that regulate e-waste management, these legislations are in place; they need to be more effectively implemented and thus unproductive (Bimir, 2020; Holtl et al., 2017). A number of non-governmental organizations and health professionals in Ghana have expressed concerns about the health and environmental impacts of the current e-waste management practices (Bimir, 2020; Martin, 2012; Agyei-Mensah and Oteng-Ababio, 2012). The local authorities need more of the required technology and infrastructural capability to deal with large volumes of e-waste generated yearly, with the majority of the e-waste informally recycled through open burning and incineration (Bimir, 2020; Awere et al., 2020).

5.1.4 India

India is considered the world's third largest contributor after China and the USA, with roughly 3.2 million metric tons of yearly generated waste, trailing only. Based on the Central Pollution Control Board of India's 2020 reports, about 1,014,961 tons of e-waste were created in 2019 and 2020 (https://science.thewire.in). E-waste in India is generated from municipal and electronic waste and imported from different countries, particularly from China.

The distribution of generated e-waste in India is as follows: 15% for household activities, 15% for the government, public, and commercial sectors, and electrical and electronic trash accounts for 70%. The problem with e-waste in India is that official recycling and disposal procedures are only limited in some cities and towns. At the same time, the informal sector is dominant in that it does not have any knowledge or awareness about the hazardous health consequences (Awasthi and Li, 2017).

The majority of e-waste is disposed of either in landfills, which receive a great deal of e-waste, or via incinerating. Both disposal techniques are done informally, which negatively affects health and contributes to environmental degradation. The spread of informal e-waste recycling, improper management, and the lack of proper technologies have intensified a significant hazard to human life and the environment.

5.1.5 Nigeria

According to the steady growth of the Nigerian economy, the spread of mobile phones, and the internet across the country, EEE has increased substantially (Andeobu et al., 2021a; Ejiogu, 2013). Therefore, the management and disposal of e-waste in Nigeria have become very significant due to the massive quantities of e-waste generated and from imported second-hand EEE (Akpeimeh et al., 2019; Jibiri et al., 2014). Nigeria has become a key destination for e-waste from high-income countries, particularly the USA and UK (Andeobu et al., 2021a; Akpeimeh et al., 2019).

Refurbished second-hand computers have a vast market share. They are regularly sold to business centers, cyber cafes, students, computer training centers, high schools, and universities (Andeobu et al., 2021a; Ejiogu, 2013). There are few infrastructures for the management and recycling of e-waste in most parts of the country. Consequently, the recycling of e-waste for resource recovery has been minimal. Hence, e-waste is disposed of in landfills, open waste dumps, burned in the open air, or disposed of in rivers and drainage (Andeobu et al., 2021a; Sthiannopkao and Wong, 2013). The Nigerian government recently designated a site for storing e-waste and has also set up a program to gather e-waste from other dumpsites to a central location. In addition, the government has also signed a memorandum of understanding (MoU) with private partners to formally recycle e-waste generated in various parts of the country (Andeobu et al., 2021a; Ejiogu, 2013).

The Nigerian government has passed several acts and legislations to manage e-waste, aiming to obligate industries to identify solid hazardous wastes unsafe to public health and the environment and carry out research on the possibilities of recycling. To control the surge of refurbished and used, EEE acts also deal with the examination of imported goods prior to shipment from their country of origin (Andeobu et al., 2021a; Adama et al., 2019; Ejiogu, 2013).

6. E-waste management

This section mainly aims to provide proposals to eliminate the negative consequences of e-waste on health and the environment in developing and least-developed countries.

Benefits of e-waste recycling

To fight poverty and eliminate unemployment in developing and least-developed countries, sustainable management of e-waste is a prerequisite to achieving these goals and obtaining economic development. Moreover, through the collection, safer recycling, and processing of e-waste, we can protect the environment and human health from hazardous e-waste emerging from burning or disposal in open landfills. E-waste would also serve as a valuable source of secondary raw materials recovery, and recycling can reduce pressure on scarce resources, contributing to production.

To sum up, recycling can provide the following opportunities:

1. Employment: Recycling of e-waste does not entail skilled labor and that is most relevant for least-developed countries.
2. Economic benefits: Economic benefits for used and obsoleted e-waste earned by e-waste collectors plus supply chain activities related to the recycling industry. Therefore, this is considered a source of income for many people in the informal sector.
3. Eliminate environmental degradation: Avoiding informal and traditional methods of e-waste disposal, such as burning hazardous e-waste or disposing of it in open landfills, will increase environmental degradation. At the same time, recycling via formal ways will provide economic benefits from valuable substances along with the disposal of e-waste either in sanitary landfills or sanitary incinerators. Figures 5 a, b, and 6 a, b display the difference between formal and informal landfills and incinerators. Figure 7 provides formal ways to dispose of hazardous e-waste.

Figure 5a. informal landfills in developing and least-developed countries

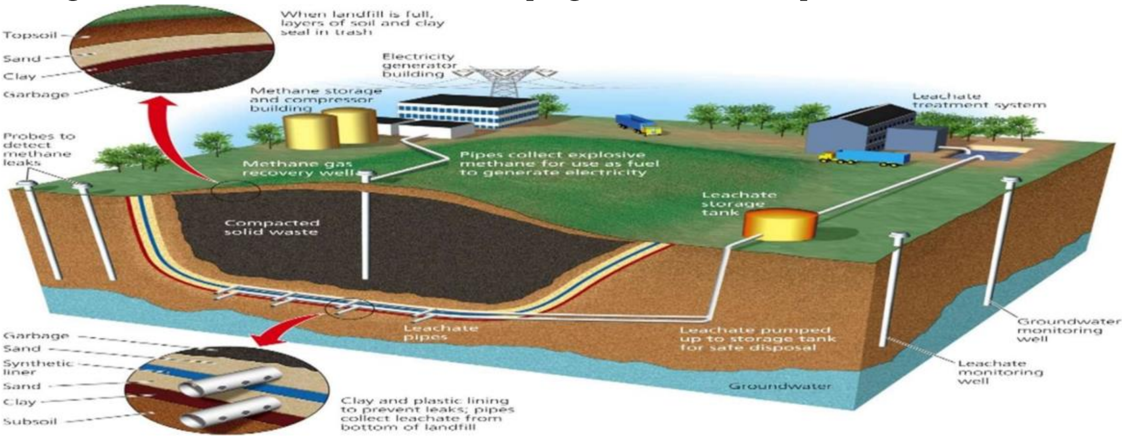

Figure 5b. Formal landfills in developed countries

Figures 5 b. and 6. b provide formal e-waste disposal in which we can protect the environment and eliminate diseases that emerge from informal disposal. Moreover, we can generate electricity from safe sources and eliminate the usage of fuel fuels that increase environmental deterioration.

Figure 6a. informal incineration of e-waste in developing and least-developed countries

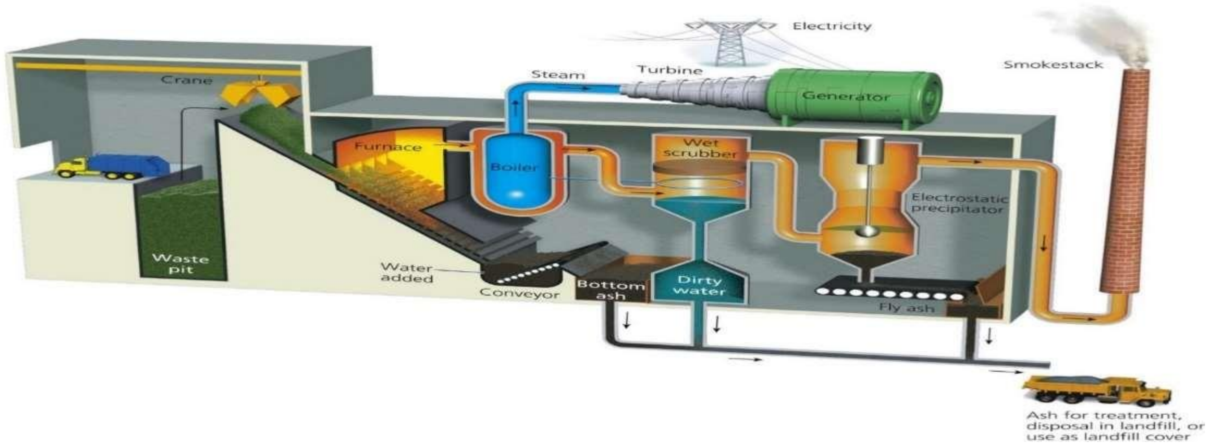

Figure 6b. formal incineration of e-waste in developed countries

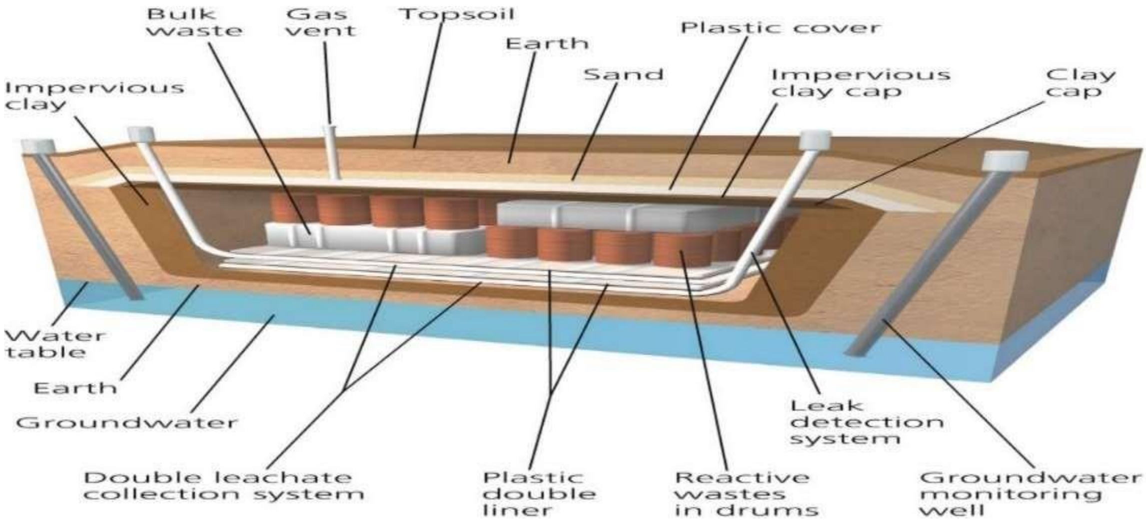

Figure 7. A formal way to dispose of hazardous e-waste in developed countries

4. Refurbishment for outdated EEE: Refurbishment of near-end-of-life equipment for sale and reuse provides cheap alternative EEE to consumers and employs a number of refurbishers, which creates new jobs.

5. Precious metal recovery for industry: The economic benefits of recovering precious metals such as aluminum, copper, brass, iron, and gold from e-waste components for industry.

6. The benefits of recovered metals over mineral mining include a reduction in the sourcing of primary raw materials such as gold, silver, and so on. Metal recovery via recycling has the following benefits:

- eliminate production cost
- eliminate the usage of energy fossil fuels, which
- eliminate pollution and improve environmental quality

- eliminate chronic diseases that emerge from informal e-waste disposal and eliminate social costs of remediation.

How to achieve effective e-waste management?

The following procedures should be implemented to obtain effective e-waste management, enhance economic benefits from recycling, eliminate environmental degradation, and eliminate negative impacts on health in developing and least-developed countries.

a. Take back the system

A take-back system is characterized as collecting utilized electronic devices to recycle or reuse and is ascribed as a critical factor of e-waste management.

b. Recycling

Isolation of valuable, reusable, and hazardous materials from EEE before final disposal is treated as e-waste recycling. Elevated recycling costs with regard to the technologies (Nadeau et al., 2008) and colossal e-waste recycling are the pivotal obstacles.

c. Disposal and reuse

The primary concern of e-waste management is to control and manage unregulated disposals and illegal landfills of e-waste at open dumpsites in developing nations. Thus, the goal is to maximize to triple R concepts for e-waste (reduce, reuse, and recycling). Disposing of e-waste in a safe area after excluding harmful materials is known as e-waste disposal. Ecologically justified disposal is a critical factor of e-waste management. Likewise, utilizing the secondhand EEE by reprocessing is usually considered as reuse.

d. Rules and regulations

improving e-waste management with effective rules and regulations entails setting laws and acts aiming to make the final treatment and landfill the last stage of the disposal process and benefit from e-waste via the reuse and recycling process.

5. Government support

- Governments in developing and least-developed countries should cooperate and set a feasible goal for managing e-waste because it is a burden on development in these countries.
- policies, strategies/management, and regulations should be integrated so as not to be conflicted to overcome e-waste issues efficiently.
- Governments should provide incentives and financing schemes for entrepreneurs to be attracted to this sector.

e. Awareness

There is an urgent need to build awareness among people about e-waste management. Lack of public sense will be problematic for efficient e-waste management practices. Manufacturers should be made responsible for improving the awareness of consumers and the general public about the threats of e-waste and the applied procedures to avoid these risks. Moreover, the producers should create awareness about the maintenance aspects of the EEE to extend the end of life such that regular recycling could be eased. Creating awareness to the end-user about the end-of-life and service activities of e-waste by providing support information. There needs to be more information about the disposal, dismantling places, recycling centers, and consumer knowledge about e-waste impacts on the environment. Finally, the lack of responsibility of the people towards the environment dries up the uncontrolled or misusing of the EEE, and informal disposal creates a significant challenge to formal recycling. In addition, different media tools have a responsibility to provide awareness programs by inviting government officials, producers, experts, and environmental volunteers to provide proper disposal techniques.

f. initiations

initiations indicate setting plans or schemes for the collection, recycling, and disposal of e-waste. Efforts start with collecting and recycling the e-waste from residential and business sectors; enterprises and individual consumers choose to send owned e-waste to formal recyclers and promote renewal and reuse.

g. Responsibility

Responsibility entails that e-waste management is a joint responsibility for manufacturers, consumers, government, and society as a whole.

h. Lack of information

Lack of information is one of the significant obstacles in e-waste management at the end of the life cycle. It is necessary to quantify the e-waste streams to counterbalance the inequalities in generations and assess the risks involved. A reliable set of information helps to evaluate or check that the e-waste streams comply with the policies set.

i. Lack of training and recycling infrastructure

The main problem in developing and least-developed countries is that the recycling operations are done manually. With the manual processes, it is tough to deal with the e-waste streams containing hazardous substances present in them. Moreover, recycling technologies are expensive and require training programs and funds to operate. For full-scale operations, there is a definite need for know-how in recognizing and handling times when the situations engage beyond the limits. Adding to this, the availability of adequate and sophisticated infrastructure should be given high priority such that efficient e-waste treatment is possible. Developed countries should support and transfer recycling technologies to developing and least-developed countries.

7. Recommendations

To achieve effective e-waste management, the following procedures should be implemented:

- Propose measures for establishing disposal and recycling systems
- Establish e-waste management scenarios provided by environment protection regulations directing producers, importers, and retailers to be bound by the cost of collecting, recycling, and reusing EEE.
- Encourage legal imports of e-waste, including non-hazardous items. Ban the importing of e-waste containing hazardous e-waste.
- Set a standard for the certification of secondhand or reusable EEE to improve trustworthiness among consumers, provide incentive-based reuse systems and awareness among consumers, and encourage reuse rather than disposal.
- EEE characterized by the Basel Convention subjected to be controlled or separated to hazardous and non-hazardous mixes.
- E-waste should be handled in line with environmentally friendly principles, criteria, and practices.
- Encourage product life extension principles such as repairing the crashed EEE rather than repurchasing new ones. This is achieved by the improvement of repairing or service centers.
- A collaborative approach of developed nations to developing countries in terms of economic and technological aspects for the active and improved e-waste management scenarios.
- Make e-waste recycling a respectable occupation for skilled people and train them to handle e-waste bundles efficiently.

8. Conclusion

The paper investigates the problem of e-waste in developing and least-developed countries along with its advantages and drawbacks on the economy, environment, and health. Then, the study provides a case study about the e-waste problem in a sample of developing and least-developed countries. Afterwards, the study handles the ways of how to manage e-waste effectively. Finally, the paper sheds light on the policy implications for the role of governments, policymakers, civilian society, and the business sector in dealing with the problem of e-waste in a way that setting rules and regulations aims to provide motivation to entrepreneurs to focus on the importance of recycling, maximize economic return of recycling, and mitigate a negative impact of e-waste on health and the environment.

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