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ELECTRONIC WASTE PROBLEM IN DEVELOPING NATIONS: MISMANAGEMENT, HEALTH IMPLICATIONS, AND CIRCULAR ECONOMY OPPORTUNITIES

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Abstract

Introduction: *Electronic waste (e-waste) has emerged as a global concern due to the exponential growth in electronic consumption and inadequate disposal practices, specifically in developing countries. Among the various dimensions of this problem, the contamination of soil with e-waste has garnered significant attention, owing to its profound implications for environmental integrity and human health.* ***Discussion:*** *The soil contamination leads to diverse ecological repercussions, encompassing disruptions in the cycling of nutrients and biodiversity, as well as the potential for contaminants to accumulate in the food chain. Effective management strategies are imperative to address this multifaceted challenge, the implementation of governmental regulations, the adoption of sustainable e-waste recycling practices, and the raising of public awareness campaigns. The circular economy holds great potential for addressing the environmental and economic challenges. To build a more resilient and eco-friendly urban future, collaborative solutions are necessary to address infrastructural, policy, and awareness issues. In many circumstances, waste management is not primarily the government's duty. Non-governmental organizations (NGOs) and the business sector actively participate in trash management efforts through public education events and charity initiatives. This significant revolution has the potential to meaningfully advance smart city development through the use of technology-driven initiatives.* ***Conclusion:*** *By proactively addressing and reducing e-waste contamination in soil, we can mitigate the effects of environmental hazards and safeguard human health from the negative consequences associated with this burgeoning predicament.*

INTRODUCTION

Electronic gadgets have played a vital position in our society in the modern period of fast technology breakthroughs, enabling unrivaled convenience, connectivity, and transformational technical capabilities (1-2). However, the exponential growth in electronic consumption and subsequent improper disposal practices have engendered a formidable environmental challenge known as electronic waste (e-waste). Some types of electronics that are most often encountered every day are televisions, refrigerators, air conditioners, computers, and mobile phones. According to the Global E-waste Statistics Partnership (GESP), e-waste volumes increased by 21% in the five years from 2014 to 2019. This expansion resulted in the production of a massive 53.6 million tons of e-waste (3). Moreover, while some developed countries have established recycling programs and regulations for e-waste management, many regions, especially in developing nations, struggle to cope with the mounting e-waste due to inadequate infrastructure and resources. Consequently, a considerable portion of discarded electronics often ends up in landfills or is improperly disposed of, posing severe environmental and health risks.

The occurrence of e-waste contamination in soil is a pervasive global problem, affecting both developed and developing nations. China has become recognized worldwide as one of the largest and most publicized e-waste disposal sites. Based on studies in

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Ghana, Tanzania and Nigeria, the accumulation comes from imported e-waste receiving large volumes of the same types of discarded European consumer products. Approximately 60,000–71,000 t of used electric and electronic equipment (EEE) were imported annually through the two main ports in Lagos in 2015 and 2016. In Nigeria, 77% of used EEE imported during this period originated from the EU. Major entry points for used EEE into Africa include the ports of Durban (South Africa), Bizerte (Tunisia), and Lagos (Nigeria) (4-5). In India and Pakistan, a similar situation arises where about 70-80% of the collected e-waste originates from developed nations. Specifically, personal computers (PCs) and laptops emerge as the primary items within the national level (6).

Analyzing the current state of e-waste contamination, identifying the pathways through which toxins enter the soil, and researching the potential consequences can provide valuable insights into the extent of the problem. In developing countries, the informal sector is playing a critical role in e-waste management. Informal recyclers recover valuable elements from electronic gadgets without sufficient safety standards, frequently in unsafe circumstances. Improper disposal practices, informal recycling methods, and the discarding of electronic devices in landfills have led to the release of hazardous substances into the soil (2,7). These substances include heavy metals, microplastics and other toxic chemicals, which pose significant risks to soil quality, ecosystem stability, and human well-being. This raises concerns about the possible transmission of pollutants to people via contaminated crops, which can result in a variety of health problems such as organ damage, developmental abnormalities, and even cancer (8-9).

Long-term exposure to e-waste-contaminated soil might have negative health impacts to human. Chronic exposure to heavy metals and hazardous chemicals from e-waste can cause respiratory difficulties, neurological abnormalities, reproductive problems, and weakened immunological function. Children, pregnant women, and communities living near e-waste recycling operations are particularly vulnerable to these health threats (3,9). Addressing e-waste contamination in soil requires collaborative efforts at several levels and as such governments and the local/regional authorities play an important role in maintaining strict waste management rules, supporting responsible recycling methods, and enforcing correct disposal processes. Public awareness campaigns, education, and advocacy can empower individuals to make informed choices about electronic consumption, disposal, and recycling, fostering a culture of environmental responsibility.

This review aims to identify the occurrence, implications, and health perspectives associated with electronic waste contamination in soil. Through collaborative efforts, including comprehensive waste management strategies, technological innovations, and societal engagement, we can strive toward minimizing the environmental and health risks associated with the escalating challenge of e-waste contamination in soil. The emergence of new technologies, such as artificial intelligence, IoT (Internet of Things), and wearable devices, leads to the creation of novel electronic gadgets. As these technologies become more integrated into daily life, the disposal of older devices further adds to the e-waste stream. Implementing circular economy concepts can help reduce e-waste by encouraging electronics repair, remanufacturing, recycling, and make the electronics sector more sustainable.

This review conducts research on e-waste pollution of soil in developing countries and focuses on the interactions between e-waste pollutants and soil, as well as research on the treatment and reuse of e-waste components. The current study employed a narrative synthesis approach to examine the origins of e-waste, assess its health impacts, and suggest solutions to mitigate its effects. A comprehensive search was undertaken across several electronic databases, including PubMed, ScienceDirect, SpringerLink, Taylor and Francis, and Google Scholar. All references from these studies were carefully reviewed, and additional relevant publications were included. The search covered the period from January 1, 2013 to June 1, 2023, and included particular keywords such as "e-waste pollution in soil," "e-waste in poor countries," "circular economy from waste," and "e-waste prevention" to locate relevant scholarly papers for inclusion in the study. Regardless of research type, epidemiological, clinical, and experimental studies reporting variables associated with e-waste exposure or health hazards connected to e-waste were carefully included and reviewed. Generic databases, such as those from the World Health Organization (WHO) or the Environmental Health Departments of developing nations, were used to obtain pertinent information. The classification of countries as developing originates from the record of World Bank as of June 2023.

DISCUSSION

Soil pollution from e-waste is frequently caused by insufficient landfill disposal methods, inadequately regulated recycling operations, burning, and hazardous dust accumulation from disintegrating e-waste (3,10-11). As a result, the soil near these dumping sites gets contaminated with dangerous compounds, posing substantial environmental and health risks. According to previous study, the majority of e-waste comes from big electronic appliances (54.2%), followed by telecommunications and IT equipment (11.8%) and consumer equipment (11.2%) (12). As indicated in equation 1, the yearly output of e-waste, abbreviated as E (kg/year), is impacted by individual item weights, M (kg), the number of items in service (N), and their average life expectancy, L (years).

$$E = \frac{MN}{L}$$

A computer normally lasts three years, during which time it generates substantially more e-waste than electric stoves and refrigerators, which have lifespans of up to ten years. Consumer preferences, purchase habits, and disposal attitudes are pivotal factors. Prioritizing cheap, low-quality, new equipment may offer short-term gains, but it can result in lasting negative repercussions for the environment and workers in the disposal process.

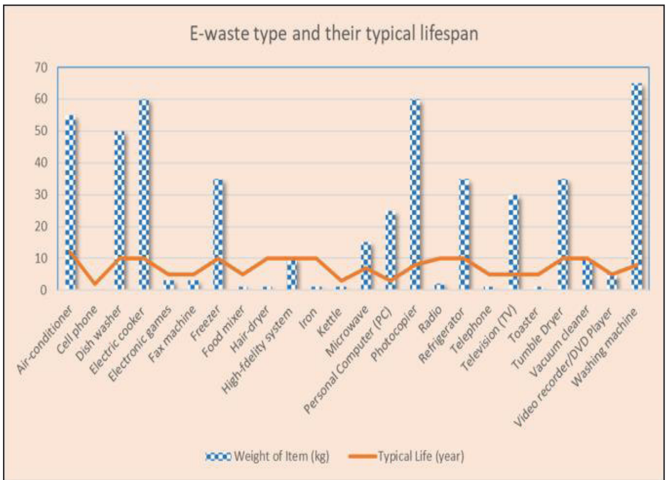

Figure 1. Electronic Devices, Including Their Weight and Expected Lifespan (75)

Figure 1 shows washing machines, air conditioning units, dishwashers, and photocopiers that surpass a weight of 50 kg. These machines have long working lifespans and need a significant amount of time for sorting activities.

Several components of e-waste separated based on component type and characteristics are shown in Figure 2. The separation process may include the disassembly of electronic equipment, which can release hazardous substances into the environment such as heavy metals (e.g., lead, mercury) and toxic chemicals (e.g., flame retardants) (9,13). In Thailand, the primary source of lead (Pb) was found to be computer monitors, which were crushed during the disposal process (11). Contaminants in soil are found through a variety of factors, including leaching from e-waste disposal sites, wind direction, erosion, and the progressive release of toxins from degrading electronic equipment. Chemical pollutants found from e-waste may distribute in the direction of the prevailing wind surrounding the waste electronic and electrical equipment (WEEE) processing plant. Various studies have provided evidence of the effect of leaching on the upper soil layer, with the potential consequence of contaminating the subsoil profile (14–16). This risk is notably heightened during the rainy season, marked by a substantial volume of rainfall. Various toxic pollutants associated with e-waste accumulation in developing countries are shown in Table 1.

Figure 2. E-waste Separation from Electronic Devices (76)

Table 1. Several Pollutants in Soil and Its Effect Associated with E-waste

Country	Pollutants	Results	Source
Ghana, Nigeria, Benin	Organic contaminants (PBDEs, TCPP, PFBS, PFBA, PFOA).	Researchers discovered that non-polar extracts derived from e-waste soil had a greater influence on COS-7 cell viability than polar extracts and elutriates.	(71)
Agbogbloshie/ Ghana	PCBs, metalloids, PBDEs, PAHs and CPs.	Concentrations of various heavy metals and metalloids were found to exceed removal requirements, with the most often discovered elements including Pb, Cu, and Zn, as well as Sb, Cd, Cr, Ni, and Ag. This discovery is consistent with the higher amounts of these metals recently discovered in the blood, urine, and hair of e-waste workers.	(50)
Pakistan & China	PAHs, PCBs and heavy metals (Cu, Pb, Zn).	The findings suggest that microbial populations at e-waste recycling facilities follow the *EisE* hypothesis. Soil characteristics such as TOC, TN, and pH, as well as the presence of organic pollutants such as PAHs, PCBs, and PBDEs, and heavy metals such as Cu, Zn, and Pb, all have an impact on the abundance, variety, and interrelationships with microbial communities.	(39)
West Bengal/ India	Toxic metals (Pb, Cr, Mn, Fe, Co, Ni, Cu, and Cd).	Children exhibited a higher non-carcinogenic risk than adults. In Cr exposure, the calculated carcinogenic risk was 6.1×10^{-7} for children and 1.57×10^{-7} for adults.	(56)
Vietnam	PAHs, MePAHs, phenanthrene, anthracene, fluoranthene, benz[a] anthracene, and benzo[a]pyrene.	The elevated levels of PAHs and MePAHs in the region is primarily due to the uncontrolled burning of e-waste and agricultural byproducts, coal, biomass combustion, and transportation activities. Also, the phenanthrene, anthracene, fluoranthene, benz[a] anthracene, and benzo[a]pyrene exceeded the maximum permissible concentrations.	(50)

Country	Pollutants	Results	Source
Delhi/ India	Toxic metals (Pb, Cd, Zn, Ni, Cu, Al, Zn, and Cd).	The study discovered the high level of soil contamination arising from the release of toxic elements in the vicinity of e-waste recycling sites that are currently in operation.	(17)
Thailand	Toxic metals (As, Cr, Cd, and Pb).	This study assessed the presence of harmful metals (As, Cr, Cd, and Pb) in water, soil, and frogs near an electronic waste disposal site. It analyzed heavy metal accumulation in three frog species and potential health risks.	(72)
Gujarat/ India	Micronutrient metal elements, such as Fe, Cu, Zn.	E-waste-tolerant bacteria (ETB) increase plant development in soils with e-waste amendments while also assisting in the movement of trace metals into the plants.	(36)
South Africa	PCBs and toxic metals (As, Pb, Hg, Cd).	E-waste is a significant source of heavy metals and chlorinated organic compounds such as As, Pb, Hg, Cd, and PCBs. These compounds are known to be carcinogenic, teratogenic, and mutagenic, especially when discharged in unmanaged landfills.	(73)
Manila, Philippines	Pb silicate, Pb chromate, and Pb(II) hydrogen phosphate	Pb was adsorbed onto goethite as oxides and carbonates, demonstrating the impacts of soil mixing and weathering. However, lead in the form of phosphate and organic compounds was only found in soil samples, showing that their formation was specific to the soil composition.	(64)
Depok, Bogor and Bekasi/ Indonesia	Toxic metals (Mn, Pb, Hg, As and Cd)	Toxic metals have been detected in residential soil near informal e-waste recycling operations. Children living in these places had greater amounts of Pb, Hg, and Mn in their hair than children living in reference sites.	(9)
Lagos, Nigeria	PBDEs	The levels of PBDEs in soils obtained from e-waste dumpsites at a depth of 0-15 cm during the first and second years ranged between 141 and 302 ngg^{-1} of dry weight for the first and second years, respectively. These high concentrations might be connected to the common practice of open burning electronic garbage.	(74)

Modern electronic devices are designed to be compact and integrated, which makes disassembly and separation of individual components extremely challenging (17). Tiny and intricately connected parts often require specialized tools and knowledge for safe extraction. Manufacturers strive to make devices thinner, lighter, and more feature packed, which leads to densely packed circuitry and intricate internal structures that make it difficult to access and separate individual components. Small components like microchips, sensors, and batteries are often soldered or glued together, requiring specialized tools and techniques for extraction without damage. For instance, a smartphone might have a single assembly containing the camera, sensors, and other functionalities. Separating these integrated modules without affecting their functionality or recyclability demands specialized expertise and tools (1,3).

Recent actions involve proposing environmental regulations, shutting down illegal dismantling workshops, and promoting control measures to reduce chemical levels, lower pollution, and decrease health risks associated with e-waste handling. In Uganda and Saudi Arabia, there is a lack of public awareness and knowledge regarding proper e-waste management and a significant proportion of obsolete electronic devices are not appropriately subjected to disposal procedures. Instead, these devices are typically retained within households and commercial entities owing to emotional affinities and a prevailing deficit of awareness regarding secure disposal protocols (18). In many countries, particularly in the African and Asian continents, there is a widespread informal e-waste sector. However, there are also licensed e-waste collectors and recyclers who employ advanced technologies. In Indonesia, private sector dominance can conflict with the government's responsibility to manage hazardous waste, including providing facilities. This issue should concern developing countries as it affects proper e-waste management and sustainability (13,19).

E-waste possesses specific traits depending on the social context, recognized by the informal recycling sector. Understanding this skill acquisition aspect benefits environmentalists and policymakers working on sustainable e-waste management (20). The efficiency of e-scrappers in managing their time is significantly affected by their aspirations, which include not just financial security but also the desire for societal acceptance and recognition. Individuals engaged in e-waste separation are often perceived as lacking specialized skills and are considered a last option for employment. As the e-waste recycling sector grows, it can become a significant source of employment, contributing to economic development.

Migrations of Pollutants in Soil

Contaminants in soil are found through a variety of factors, including leaching from e-waste disposal sites, wind direction, erosion, and the progressive release of toxins from degrading electronic equipment. Chemical pollutants found from e-waste may distribute in the direction of the prevailing wind surrounding the waste electronic and electrical equipment (WEEE) processing plant. Soil samples demonstrate an enhanced germanium (Ge) concentration in places where the wind originates mostly from the emitter position (21). Various studies have provided evidence of the effect of leaching on the upper soil layer, with the potential consequence of contaminating the subsoil profile. This risk is notably heightened during the rainy season, marked by a substantial volume of rainfall (22-23).

According to numerous studies and reports by environmental agencies such as the United Nations Environment Programme (UNEP) and the Basel Convention, e-waste contains elevated levels of heavy metals like lead (Pb), mercury (flame retardants), cadmium (Cd), and chromium (Cr), stemming from the composition of electronic devices (22,24-25). Improper disposal methods, such as landfilling or incineration, lead to the release of these hazardous elements into the environment. As e-waste breaks down over time, heavy metals are leached into soil and water sources, posing severe risks to ecosystems. The mechanism of toxicity of heavy metals found in e-waste involves various pathways through which these substances interact with biological systems, causing adverse effects on both the environment and human health. Some heavy metals, like Hg and Cd, have the ability to bioaccumulate in organisms; they accumulate in tissues over time, leading to higher concentrations in organisms higher up the food chain through biomagnification (26).

Among the compounds found in e-waste dust, Bisphenol A (BPA) is one of the predominant substances, along with its analogs such as Bisphenol F (BPF), Bisphenol S (BPS), Bisphenol S IP (BPSIP), and Bisphenol AF (BPAF) (27). BPA is a chemical compound commonly used in the production of polycarbonate plastics and epoxy resins, often found in electronic devices such as computers, circuit boards, and plastic casings. Moreover, methods like incineration or mechanical shredding, can release toxic gases such as dioxins, furans, polychlorinated biphenyls (PCBs), and volatile organic compounds (VOCs) into the atmosphere. These gases are hazardous pollutants known for their toxicity (28–30).

E-waste elements have the potential to cause changes in soil physical qualities, such as compaction and textural changes, resulting in decreased water penetration, increased surface runoff, and increased erosion susceptibility. These consequences can make root development difficult and limit plant access to crucial nutrients and moisture. Furthermore, the proclivity of plant roots to absorb e-waste toxins such as heavy metals and chemical compounds raises worries about possible bioaccumulation (21,31). These pollutants are persistent in soil matrices, with some remaining for decades, increasing their long-term impact on ecosystems. Significantly, these contaminants can leak into groundwater, expanding the contaminated footprint and posing dangers to both surface waters and aquatic ecosystems, including possible impacts on human drinkable water supplies (32).

The hazardous substances persist in the soil for extended periods, impairing soil fertility and disrupting essential soil microorganisms that support plant growth (21,33). This degradation of soil quality not only affects agricultural productivity but also poses risks to environmental stability. Furthermore, the pollutants from contaminated soil can be absorbed by plants, leading to bioaccumulation within the food chain, ultimately raising concerns for human health as consuming produce grown in contaminated soil could lead to the intake of harmful substances. Soil-dwelling organisms, including microbes and invertebrates, play critical roles in maintaining soil fertility and ecological balance (34–36). It can hinder essential soil processes, such as nutrient cycling and decomposition, which are fundamental for sustaining healthy ecosystems. The disruption of these processes affects the growth and health of plants, reducing agricultural productivity and altering natural habitats for various organisms (37-38).

Negative Impact on Plants and Animals

The continued use of landfill practices and insufficient infrastructure in developing nations leads to a range of issues concerning the management of e-waste. Several elements present in e-waste consist of substances with enduring characteristics that pose health and soil fertility risks. Since soil serves as a medium for both plant growth and the survival of microorganisms, its condition significantly impacts the sustainability of the environment and the stability of the food chain (15,31,39). Disassembly of hardware resulting from temporary separation of the collector will inhibit the entry of oxygen and sunlight into the soil, resulting in subsidence of the surface plants. During the rainy season, contaminants will be carried away by stagnant water, thus spreading to the recycling area (15-16,40).

Plants may exhibit symptoms such as chlorosis (yellowing of leaves), necrosis (tissue death), reduced leaf size, and overall stunted growth (41-42). These effects can severely impair the plant's ability to photosynthesize and thrive. The pigment is vital for photosynthesis, and its reduction due to e-waste pollutants disrupts the plant's ability to produce energy, negatively impacting growth and productivity. E-waste pollutants can interfere with cell division and expansion processes in plants, resulting in smaller and distorted leaves. In turn, reduced leaf size diminishes the plant's surface area for photosynthesis, limiting its capacity to capture sunlight and synthesize the nutrients necessary for growth (28,36,43-44). Photosynthesis problems and plant productivity disrupt nutrient cycling, carbon sequestration, and habitat provisioning, affecting the stability and functioning of the entire ecosystem.

The presence of heavy metal contamination and acidic percolation can lead to soil infertility by reducing the availability of total organic matter (39,45). Compared to residential areas, the amount of bioaccumulation for polybrominated diphenyl ethers (PBDEs) and polychlorinated biphenyls (PCBs) derived from electronic fragments is significantly greater. PBDEs have been widely used for the last 20 years as flame retardants in polymers for electronics, while PCBs historically served as coolants and lubricants in electrical equipment. An increase in PBDE levels is reported to have led to an increase in PBDEs concentrations in rice in Changzhou, China (29). Likewise, results from a similar investigation demonstrated that more than 90% of the aggregate 26 types of PCBs were identified in the soil of unregulated e-waste recycling sites in India (28).

An analysis of food chains in communities situated near dump sites reveals alarmingly elevated concentrations of toxic chemicals in food products, particularly eggs (46). Chemical contaminants, particularly dioxins, PCBs and metals, influence egg contamination primarily through the bioaccumulation process in animals (31,47). Animals accumulate dioxins from contaminated vegetation and soil they ingest and when poultry and other food animals are fed products with higher concentrations of these contaminants on polluted soil, contamination above the background level occurs. The primary sources of dioxin contamination in eggs and bird tissues have been shown to be the various feed ingredients. Numerous studies from different countries have since indicated that soil significantly contributes to the dioxin contamination of laying hens and eggs, primarily occurring in outdoor poultry settings, granting birds access to outdoor areas where they can consume contaminated plants, insects, and soil, especially in free-range or smaller flocks (30,48).

Adverse Health Effects in Vulnerable Populations

Vulnerable populations, including children, pregnant women, the elderly, informal workers, and disadvantaged communities, face significant risks from exposure to toxic chemicals in e-waste-polluted soil. These groups often live near areas where e-waste is improperly disposed of or recycled informally. This proximity increases their chances of being exposed to harmful substances seeping from discarded electronics into the soil. Children, due to their behavior of touching objects and playing on contaminated ground, are especially vulnerable (3,49). Their smaller size and weight compared to adults make them more susceptible to the harmful effects of pollutants. As their bodies are still developing, exposure to toxic substances during critical growth stages could disrupt normal physiological processes and potentially lead to long-term health issues. This is proven by previous studies conducted in Indonesia and Vietnam, where children living around informal waste recycling were found to have a high level of carcinogenic risk from exposure to heavy metals such as Pb, Cr, As and Hg (8,9). In a study conducted in Ghana, researchers found the presence of specific elements like Pb, Cd, Rb, Eu, and Tb in the blood of e-waste recyclers is linked to a significant decrease in their hemoglobin (Hb) levels (50). Exposure to metals resulted in an increase in mitochondrial DNA copy number (MCN) and raised telomere length (LOT), along with elevated levels of metals in the blood. Importantly, adverse health effects persisted even after the shutdown of e-waste dismantling operations (25).

The threat posed by e-waste emerges as a pressing concern, specifically impacting informal laborers and nearby inhabitants, accentuating apprehensions regarding its adverse effects on both health and the ecosystem. In numerous geographical locales, the close proximity of e-waste disposal sites to residential areas heightens the potential for exposure through various pathways, such as ingestion via food sources and direct contact with contaminated objects (11,51). This precarious adjacency amplifies the likelihood of hazardous pollutant emissions into the surrounding environment, thereby exacerbating health risks for local communities and individuals engaged in informal e-waste management activities. In Pakistan, waste sorting, including e-waste, involves workers from low-income countries. These informal recyclers often face issues like unpaid leave, lost wages, and difficulties paying for medical care after workplace accidents due to a lack of personal protective equipment (6).

A high accumulation of organic contaminants and metals was found in the bodies of e-waste separation workers there is high significance between contaminant level in the body and working time. According to the findings of a previous study involving workers engaged in informal recycling activities in Cotonou, Africa, the incidence of respiratory symptoms was higher in the exposed group than in the unexposed group, with rates of 33.1% and 21.6%, respectively. Working with e-waste has been associated with an increased prevalence of respiratory symptoms and an increased risk of deterioration in both FEV1 (Forced Expiratory Volume in One Second) and FVC (Forced Vital Capacity) which is related to the potential impairment of lung function, with a particular emphasis on the manifestation of restrictive respiratory disorders (52). The manual separation and handling of electronic waste by workers exposes them to the inhalation of particulate matter (PM). Elevated exposure raises the probability of these workers experiencing symptoms related to respiratory issues, circulatory problems, and allergies.

Research examining the impact of e-waste exposure on pregnant women has revealed concerning correlations between engagement in e-waste recycling activities and adverse health outcomes for both the mother and the developing fetus (5). These studies have identified associations between e-waste exposure and increased risks of miscarriage and stillbirth, indicating that pregnant women involved in handling electronic waste may face a higher likelihood of experiencing these tragic outcomes. Moreover, exposure to e-waste pollutants during pregnancy has been linked to potential consequences on the neurological development of the fetus. Thyroid disturbances during pregnancy can have detrimental effects on both maternal health and fetal development, potentially leading to complications in pregnancy and affecting the health of the newborn (53–55).

The methodical process of deconstructing electronic equipment at e-waste disposal plants exposes both employees and nearby communities to a variety of harmful metals (10,22,56). Despite their silent existence, they constitute a significant and insidious threat to the health and well-being of individuals with the toxic effects of these metals increasing the risk of future cancer and cardiovascular disease, especially among those who do not adopt personal preventative measures (17).

Strategies and Current Regulations

E-waste management is a multidimensional task that extends beyond simply having the physical infrastructure and technologies for disposal and recycling. It also involves educating the community as customers. Recent actions have involved proposing environmental regulations, shutting down illegal dismantling workshops, and promoting control measures to reduce chemical levels, lower pollution, and decrease health risks associated with e-waste handling. In Uganda and Saudi Arabia, there is a lack of public awareness and knowledge regarding proper e-waste management. A significant proportion of obsolete electronic devices are not appropriately subjected to disposal procedures and, instead, these devices are typically retained within households and commercial entities owing to emotional affinities and a prevailing deficit of awareness regarding secure disposal protocols (57).

In many countries, particularly in the African and Asian continents, there is a widespread informal e-waste sector. Unfortunately, there are also licensed e-waste collectors and recyclers who employ advanced technologies. In Indonesia, private sector dominance can conflict with the government's responsibility to manage hazardous waste, including providing collection facilities. This issue should concern developing countries as it affects proper e-waste management and sustainability (13,19). Finding a balance between the private sector and government roles is crucial for effective e-waste management.

The establishment and implementation of explicit regulations concerning the management of e-waste are crucial, given its current classification as conventional household waste, lacking the mandate for specialized handling. However, the nature of e-waste mandates the implementation of precise and customized treatment methodologies. Many regions categorize electronic waste under general household waste regulations, treating it similarly to regular garbage. However, this classification often overlooks the hazardous materials present in electronic devices, such as Pb, Hg, Cd, and flame-retardant chemicals (8,25). As a result, there might be a lack of specific regulations mandating proper handling, collection, recycling, and disposal. E-waste possesses specific traits depending on the social context, as recognized by the informal recycling sector. Understanding this skill acquisition aspect benefits environmentalists and policymakers working on sustainable e-waste management (20). The efficiency of e-scrappers in managing their time is significantly affected by their aspirations, which include not just financial security but also the desire for societal acceptance and recognition (58). Individuals engaged in e-waste separation are often perceived as lacking specialized skills and are considered a last resort for employment. Consequently, many of them may not possess fundamental knowledge in this field. Increasing sorting capacity in e-waste management creates job opportunities for individuals involved in the sorting process; therefore, as the e-waste recycling sector grows, it can become a significant source of employment, contributing to economic development (18,58-59).

There are a variety of rules, regulations, and policies that govern e-waste management in various regions or jurisdictions. Examining e-waste policies involves assessing their effectiveness, alignment with best practices, and impact on reducing e-waste-related environmental and health risks. Policies that apply more broadly will force and influence many people (6).

For example, since 2000, the Luqiao government has regulated the e-waste recycling industry to protect the environment. Small recycling facilities were closed, and qualified ones relocated to a dedicated industrial park, focusing on solid waste recycling like old steel/iron. After a decade of effort, primitive e-waste recycling has been eliminated (34). The local pre-processing concentration of e-waste management in Taiwan has helped minimize treatment costs, particularly transportation and labor expenses. This approach may be used in regard to domestic systems with no recycling facilities, as well as international systems using the extended producer responsibility concept to collect items for recycling (60).

The collaboration between the government, non-government organizations (NGOs), and environmentalist holds significant potential in sharing the burden of managing e-waste while educating the general communities. Thus far, society has been primarily advised to segregate waste and reduce excessive consumption or usage of electronic products (61-62). NGOs and environmentalist can work alongside government initiatives to conduct educational campaigns. These programs can highlight the dangers of improper e-waste disposal and emphasize the importance of responsible recycling practices. They can engage directly with communities, organizing workshops, seminars, and interactive sessions to educate people about proper e-waste handling. This includes showcasing the environmental and health impacts of burning e-waste and encouraging the adoption of sustainable alternatives. NGOs can aid in building the capacity of local communities, enabling them to set up small-scale recycling initiatives or collection centers.

Providing knowledge about nutrition and enhancing healthcare accessibility is also essential in communities affected by e-waste, as a well-balanced diet can aid in counteracting the adverse health effects associated with metal exposure, particularly those related to hemoglobin levels. Adopting a diet rich in iron and protein can play a pivotal role in restoring and sustaining overall health (50). Consuming vegetables grown in areas where e-waste processing takes place could present a notable health risk due to potential contamination and plants or other sources of protein obtained around e-waste processing areas should be avoided because they contain toxins that can be adsorbed in the body through the ingestion route (11,51).

Circular Economy Prospects

A circular economy aims at maintaining product materials at their optimal state by distinguishing between technological and biological cycles. Currently, these efforts are mostly focused on cost-cutting measures such as raw material reduction, eco-friendly goods designed for simple disassembly and reuse, the use of recyclable materials, and the extension of product lifecycles through repair and recycling. Circular policies should capitalize on the strengths and weaknesses of the present linear system. The projection model used to evaluate the recycling impact on Circular Bioeconomy (CirBioeco) suggests that, by 2030, about 51,833 tons of copper and 58 tons of gold will be re-circulated for the manufacture of virgin metals/raw materials, while the recycling rate of accumulated e-waste will remain at 20% (63). In Indonesia, there is potential to recover valuable materials from e-waste, including 50.8 kilotonnes of copper, 41 tonnes of silver, 7.5 tonnes of gold, 0.7 tonnes of platinum, and 2.4 tonnes of palladium. About 895 kilotonnes of iron/steel and 1.8 kilotonnes of solder could be reclaimed. The data highlight the significance of responsible e-waste management for both environmental and economic reasons (13).

Healthy soil is essential for food production. Soil pollution can lead to contaminated crops and reduced agricultural productivity. But, by mitigating soil pollution through circular economy practices, we help ensure food security and the availability of safe and nutritious food (35,64). This resource-efficient approach effectively reduces the necessity for extensive resource extraction, a practice that often results in soil degradation when conducted unsustainably. Moreover, the adoption of responsible materials management strategies across the entire lifecycle of electronic devices, encompassing eco-conscious design and the proper management of end-of-life stages, substantially contributes to the preservation of soil health. The conscientious handling and disposal of toxic e-waste materials serve to mitigate the peril of soil contamination. Furthermore, circular economies stimulate innovation in environmentally friendly technologies, potentially giving rise to electronic devices with diminished ecological footprints concerning soil impact (65).

To address the rising problem of e-waste, all parties concerned must grasp and utilize the benefits of the circular economy idea. Figure 3 represents the circular economy approach in the European Union. The life cycle of electrical and electronic equipment (EEE) begins with production and usage, but often these products are discarded before their natural expiration. Upgrading drives this disposal more than product expiration. This shift to used electrical and electronic equipment (UEEE) in the second stage is influenced by events like the launch of new gadgets, leading to the abandonment of older devices. In the second stage, the crucial decision determines whether items become waste electrical and electronic equipment (WEEE) or get repaired and reused in the secondhand market. Previous study has introduced an alternative framework for evaluating the life cycle of electrical and electronic equipment (EEE) (59,65). In the urban centers of India, a shift from a linear to a circular economy is transforming e-waste management.

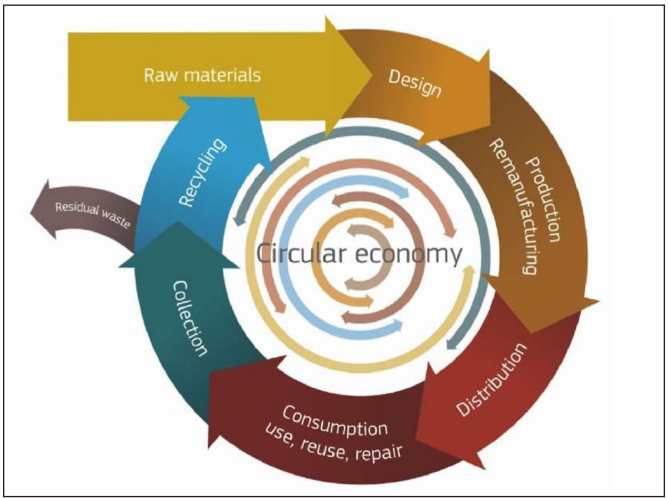

Figure 3. Circular Economy Concept in Europe (59)

The linear model, prevalent for years, involved resource extraction, product manufacturing, and eventual disposal, leading to resource depletion and environmental harm. However, the circular economy now prioritizes sustainability by promoting resource recycling and extended product life cycles, reducing waste and environmental impact. This shift represents a significant advancement in electronic waste management in India (10). Figure 4 visually illustrates this model.

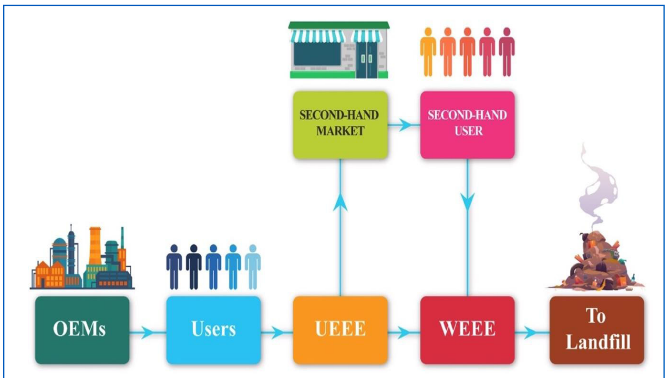

Figure 4. The role of Used Electrical and Electronic Equipment (UEEE) within the life cycle of Electrical and Electronic Equipment (EEE) (77)

The assumptions form the foundational principles of the model, providing a structured framework for analyzing the life cycle of EEE. In numerous advanced countries, although there is evidence of the existence of stores selling secondhand electronic devices, the demand for these used devices often remains restricted due to technical regulations or rapid technological obsolescence. Consequently, within this model, components that can be recycled are indeed recycled, while other components ultimately find their way into the e-waste stream. Countries like Ghana, Rwanda, Nigeria, and South Africa have unveiled policy frameworks aimed at enhancing e-waste management, which includes the implementation of the Extended Producer Responsibility (EPR) policy (65). Governments and private investors are increasingly drawn to companies and projects aligned with circular economy principles and investments in circular business models, eco-innovations, and sustainable technologies are gaining traction due to their potential for long-term profitability and positive environmental impact.

The sorting process classifies e-waste into distinct categories based on the material composition of electronic components, encompassing metals, plastics, and electronic circuits, with the objective of facilitating subsequent recycling and reuse processes (22). This approach aligns with circular economy principles and aims to mitigate the environmental impact of e-waste through resource conservation and sustainable materials management. Concurrently, the promotion of e-waste recycling and the advocacy of the "3 Rs" principle—Reduce, Reuse, Recycle—constitutes an integral facet of comprehensive e-waste management strategies. It entails reducing e-waste generation through conscientious consumption patterns, reusing functional electronic devices, and recycling constituent materials such as printed circuit boards and metal components. This multifaceted approach serves to minimize the environmental footprint of e-waste, preserve finite resources, and foster a scientifically informed, sustainable, and ecologically responsible framework for e-waste management. It empowers stakeholders to make informed decisions in the pursuit of environmental sustainability in the realm of e-waste (33).

In a circular economic framework, the principal emphasis lies in the retrieval of materials from discarded electronic devices to reintegrate them into the production cycle for new commodities. This approach significantly diminishes the requirement for pristine natural resources and mitigates the environmental ramifications associated with the extraction and processing of raw materials. Designing electronic gadgets with heightened durability, adaptability for upgrades, and facilitation of easy repairs effectively elongates their operational life cycle. Encouraging consumers to engage in device repairs or upgrades rather than premature replacements serves as a pivotal strategy in curbing the generation of electronic waste (19,59). Additionally, there exists a prudent opportunity to resell specific equipment and garments that remain in pristine condition, aimed at protracting their utility and curbing waste accumulation.

Holding manufacturers responsible for the end-of-life management of their products is a concept known as Extended Producer Responsibility (EPR). To meet their EPR obligations, manufacturers invest in research and development for more efficient and environmentally friendly recycling methods. This can lead to technological advancements in recycling processes, making it easier and more cost-effective to extract valuable materials from discarded products. Manufacturers bear the financial responsibility for managing their products at the end of their useful life, which creates a financial incentive for companies to design products that are more durable, easily repairable, and suitable for recycling, as they can potentially save costs associated with disposal and waste management. Governments or regulatory bodies also may provide tax reductions or financial incentives as a reward for manufacturers who effectively manage their products' end-of-life phase. This can include implementing take-back programs, investing in eco-design practices, or achieving specific recycling or waste reduction targets (12,19,35).

Embracing circular economy principles fosters the establishment and expansion of industries centered on repair, recycling, and remanufacturing. Skilled jobs emerge in these sectors, encompassing roles such as technicians for repairing electronic devices, specialists in material recovery and recycling, and experts in remanufacturing processes. Additionally, positions in research and development for innovative recycling methods also come into play. As such, the transition to a circular economy encourages entrepreneurial ventures, where innovative business models emerge to cater to the growing demand for repairing, refurbishing, and repurposing products (13,66). Entrepreneurs seize opportunities to develop businesses focused on sustainable practices, such as creating platforms for selling refurbished electronics or initiating local recycling initiatives.

The growth of repair, recycling, and remanufacturing industries necessitates, however a skilled workforce. As these sectors expand, there is an increased demand for individuals with specialized knowledge in sustainable resource management, materials engineering, and circular design principles. This demand leads to the development of training programs and educational initiatives focused on these areas (52,66-67). Shifting the perception of waste from being a disposable commodity to a potential resource stimulates the development of value chains centered on recycling and reusing materials. The circular economy's emphasis on sustainable design and product life cycle management contributes to creating healthier living environments aiming to design products with fewer toxic components, ensuring that products are safe throughout their lifespan. Moreover, reduced waste generation and better waste management in communities lead to cleaner and safer living spaces, benefiting overall public health. This has begun to be promoted in Indonesia, Sri Lanka and India, where the existence of waste banks and technology-based platforms has helped many households and institutions to process e-waste and other waste to be monetized and managed based on the concept of a circular economy addressing the abundance and accumulation of e-waste waste so as to reduce contact and problems with the environment that threaten human health (62,68–70).

CONCLUSION

The alignment of mismanagement issues, health impacts, and circular economy opportunities with the research objectives underscores the profound potential of adopting a circular economy framework to tackle the pressing challenges posed by e-waste in developing nations. By focusing on resource efficiency, promoting sustainable consumption patterns, and advocating for the reuse, repair, and recycling of electronic products, the circular economy presents a compelling solution. Its multifaceted approach not only generates economic advantages but also significantly mitigates environmental repercussions.

However, the successful implementation of the circular economy model in these countries necessitates strategic investments in infrastructure, targeted awareness initiatives, and the formulation of policies that account for the unique circumstances of each nation. Industries play a pivotal role in the generation and management of electronic waste; by recognizing the inefficiencies in the current linear "take-make-dispose" model, industries stand to benefit significantly from transitioning toward circular economy principles. This underscores the criticality of adapting the circular economy paradigm to suit individual contexts, thereby solidifying its potential as an effective strategy for addressing the burgeoning e-waste crisis in developing nations. Further exploration and research in both academic and policy domains are imperative to fully realize the transformative impact of the circular economy approach in combating e-waste issues.

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