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SYSTEMATIC REVIEW

Toxic Tides of Electronic Waste: A Comprehensive Assessment of Health and Environmental Impacts

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ABSTRACT

E-waste has emerged as a crucial environmental concern for many governments globally as a result of the quick development in the usage of electronic and electrical equipment worldwide. According to several studies, dangerous compounds in electronic waste may result in environmental tragedies and health issues for people if proper recycling practices are not adopted. This justifies a reconsideration of the current e-waste management procedures. This report summarizes the advancements made, identifies areas for improvement, and critically evaluates earlier studies on the production of e-waste and management strategies of the key Asia Pacific countries that produce digital garbage. This is done in light of the nation's growing e-waste generation and the significance of e-waste management. The digital era has ushered in unprecedented convenience and innovation, but it has also given rise to a significant challenge: e-waste. The serious effects of inappropriate e-waste disposal on the environment and human health are highlighted by this in-depth investigation. It emphasizes the urgent need for responsible practices, global collaboration, and innovative, sustainable solutions to address this complex issue and ensure a healthier, more sustainable future.

Keywords: Asia Pacific, challenges, environmental management, e-waste, health impacts

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INTRODUCTION

The Asia Pacific region is characterized by its high population density and quick pace of development, making it one of the most prominent and dynamic areas on a worldwide scale. Furthermore, the rapid industrialization observed in numerous nations within this region may be attributed to the availability of a relatively low-cost labour force, which has been further facilitated by the inflow of foreign direct investments. The electrical and electronics industry has experienced a notable transformation due to advancements in technology and commercial developments, resulting in major benefits for this sector. The presence of dangerous compounds in electrical and electronic equipment poses a significant threat to both the environment and human health, hence exacerbating the ongoing climate crisis. Despite its role in improving living conditions, the necessity of such equipment cannot be overlooked. The increase in the quantity of electronic garbage (e-waste) can be attributed to the escalating demand for electronic products and the pursuit of greater financial gains.[1]

The escalating quantity of electronic garbage (e-waste) is a significant concern for both the environment and local populations worldwide due to the incorrect disposal practices associated with e-waste. The electronic waste in question leads to the emission of perilous compounds that have detrimental effects on both human health and the environment. The yearly production of electronic garbage (e-waste) is seeing a significant increase. In the year 2019, the global production of electronic garbage exceeded 50 million cubic meters. The Asia Pacific area alone accounted for the production of 24.9 million tonnes of e-waste, constituting a significant portion of the total global amount. The creation of e-waste increased at a rate three times faster than the growth of the world population. By the year 2030, it is projected that the global production of electronic garbage (e-waste) will exceed 74 million tonnes.[2] The rate of recycling, however, is not commensurate with the quantity. Furthermore, a significant portion of the generated electronic trash is now being directed towards landfilling, a prevalent approach to e-waste disposal on a global scale. The

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primary challenges associated with current e-waste management practices include insufficiently efficient trash collection and recycling systems, as well as a lack of mechanisms to hold electrical and electronic equipment (EEE) manufacturers accountable for the disposal of end-of-life products. The inappropriate implementation of e-waste recycling practices might potentially result in significant adverse consequences for both the environment and human health.[3] Although many studies discuss electronic waste generation, recycling, treatment, and environmental oversight, only a few have specifically looked at how electronic waste in selected Asia Pacific countries affects both human health and the environment.

Second, accordingly, more work is required to ensure wiser and more sustainable worldwide production, consumption, supervision, and disposal of e-waste since many nations, especially those in the Asia Pacific area, are not managing e-waste created effectively.[4] More corporate efforts are required to address the growing e-waste problem through adequate research and training. It is also noted that more e-waste is created than is securely recycled in many nations throughout the world. The problems with managing e-waste in today's digitally linked world are mostly caused by the unsustainable ways we now make, use, and discard electronic gadgets. By creating the essential, needed, and required e-waste legislation, implementing proper e-waste management techniques would help to attain sustainable development goals and lessen the global climate catastrophe.

Thirdly, there have been studies and conversations about the production and handling of e-waste for a long time. However, the issues and difficulties associated with the creation and treatment of e-waste continue.[5] This review seeks to evaluate the current electronic waste (e-waste) management practices in the major e-waste-producing nations of the Asia Pacific region, aiming to mitigate the adverse impacts on the environment and human health caused by improper recycling and disposal. Through a careful examination of existing research on e-waste generation and environmental management in different countries, the review identifies challenges, assesses progress, and suggests management approaches and policy frameworks to address e-waste issues. This significantly decreases the health and environmental problems associated with e-waste.[6]

MATERIALS and METHODS

A comprehensive literature search was conducted across Google Scholar, PubMed, and Web of Science databases for studies published between January 2010 and June 2024. The following search terms and Boolean operators were used, and the first assessed date was 29th of January. The terms used are: “e-waste” OR “electronic waste” OR “waste electrical and electronic equipment”) AND (“Asia Pacific” OR “India” OR “China” OR “developing countries”) AND (“environmental impact” OR “health hazard” OR “management strategies”). Only peer-reviewed, English-language articles were included. Conference papers, editorials, and grey literature were excluded. Manual screening of reference lists of included studies was also performed to identify additional relevant articles. Two independent reviewers screened all titles and abstracts for relevance. Full-text screening was performed for potentially eligible studies. Any disagreement between reviewers was resolved through discussion and consensus.

Additionally, manual searches of the cited papers were done as additional article research. In order to screen all referenced publications in accordance with PRISMA rules, the citation manager application was used to enter all cited articles. To prevent biased research, several keywords and tactics were chosen. The investigation methodology specified during the literature review was used to filter the publications. Several publications were chosen for a more thorough investigation after the titles and abstracts of the papers were examined. Some of them were excluded following a thorough investigation, while the remainder were chosen for inclusion in this systematic review. We excluded 55 (Fig. 1) redundant and unrelated papers that did not primarily focus on e-waste after thoroughly inspecting the research and conducting the literature review. The objective of this approach is to gain an understanding of domestic e-waste output, connect it with regional and international production, and demonstrate the effectiveness of e-waste treatment in contributing to environmental sustainability. Additionally, we described the chosen model for estimating and forecasting. This study primarily emphasizes the economic, environmental, and social aspects of sustainable management, with a particular focus on the consumer market and the supply chain network. However, more documentation about the manufacturing, collection, and handling of e-waste is needed.

PRISMA Flow Chart

The PRISMA 2020 flow diagram (Fig. 1) summarizes the selection process. A total of 2,990 records were initially identified through the database search. After removing duplicates, 2,450 records were taken forward for screening. Out of these, 420 articles were screened by title and abstract, and 232 were excluded at this stage. The remaining 188 articles were assessed in full, but 154 did not meet the required quality standards and were therefore excluded. In the end, 34 studies were included in the qualitative analysis.

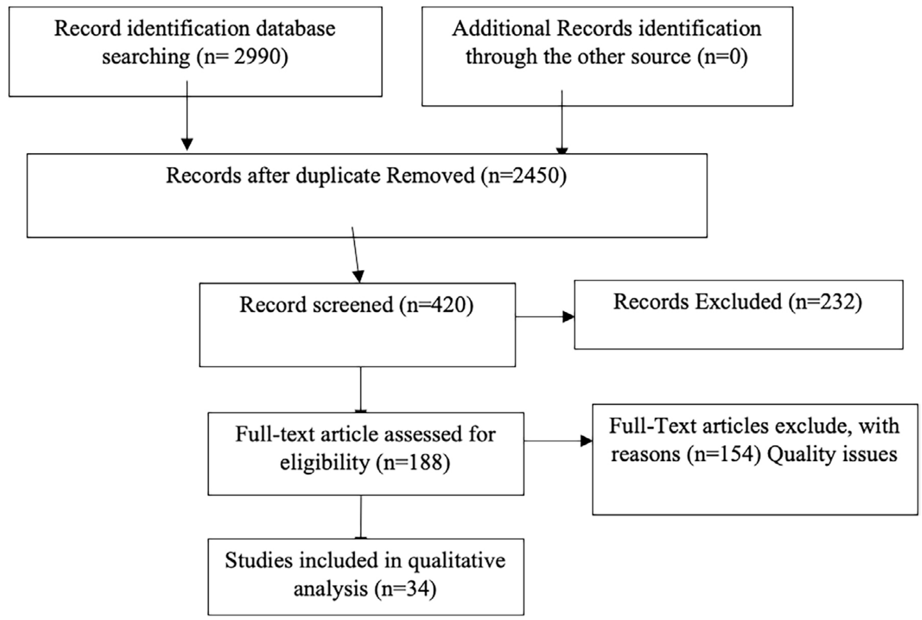

Figure 1. Prisma chart

Production of E-Waste Worldwide

In 2021, 53.6 million metric tonnes of electronic waste were generated worldwide, with an average annual growth rate of 2.5 Mt, according to the World E-Hide Monitor. In 2014, 44.4 Mt of electronic waste was produced—a more than 20% increase over the year before. It indicates hazardous conditions. The USA generates 13.1 Mt of electronic waste annually, or 13.3 kg per person—more than any other country in the survey. However, only two metric tonnes of all electronic waste are appropriately handled, meaning it is legally collected, recorded, and recycled, in accordance with US EPA laws.[7] According to a study in the USA, an American family uses more than 20 pieces of electronic equipment on average. With 42.3% of the 12 Mt of generated e-waste, Europe appears to operate the most structured and effective electronic waste handling processes. Asia produced the most e-waste, yet only 2.9 Mt of it was recycled. E-waste creation per capita worldwide is highest in Europe. India produces the most e-waste, followed by the United States and China, with China producing 10.1 Mt—one of the greatest amounts. It contributes 7.3 kg globally, whereas its per capita obligation is 2.4 kg. The amount of electronic waste released has increased by 58% in the last nine years. With 595 kt, or 21% of the region, Saudi Arabia is the leading producer of e-waste among Arab nations, according to the United Nations E-waste Monitoring. Currently, only 22% of the hazardous waste produced is handled; the remainder is untreated or left over.[6] Most of the e-waste is generated by developed countries and illegally exported to underdeveloped and developing countries, including India, China, Brazil, Ghana, Nigeria, and Pakistan.[8] The social, economic, and environmental factors are used to organize the technical parts of waste electrical and electronic equipment and the sustainability evaluation.[9] First-level e-waste treatment is shown in Figure 1.[10]

To address resource management, financial stability, policies, environment, and user inclusion, economic statistics, consumer behaviour, and national-level e-waste data are used to generate the parameters—whether certain metrics are both quantitative and qualitative. In the short term, models can also be useful for improving preparedness and precisely predicting the growth of e-waste in the region. Grey model e-waste forecasting, for example, allows for an accurate and imaginative prognosis.[11]

The current level of electronic waste manufacturing in Saudi Arabia is exceedingly hazardous. That necessitates a strong and concrete e-waste management and framework of regulations spanning from international trade to garbage collection at the municipal level, according to a comparative analysis of international e-waste management models. Social awareness and raising public perceptions of the problem's importance can both contribute to improved outcomes and boost the effectiveness of the aforementioned strategy. The most widely used and applied frameworks for behaviour analysis in the management of e-waste are the Extended

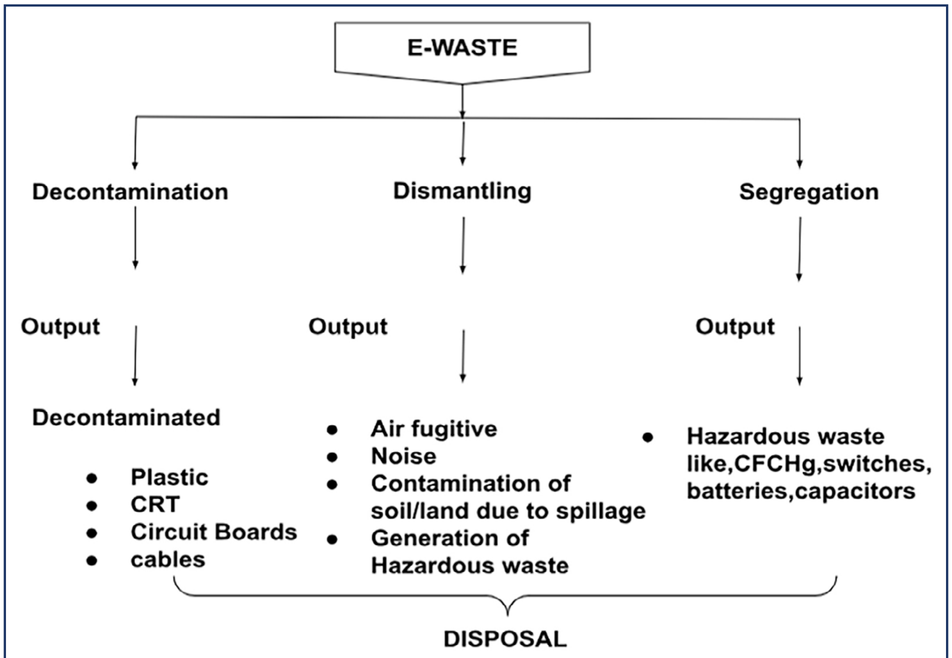

Figure 2. 1st level e-waste treatment

Producer Responsibility and Value-Belief-Norm Theory. By facilitating the efficient conversion of waste prior to landfilling, these frameworks will improve the handling of electronic waste operations and encourage ecological sustainability.[12]

Electronic Waste Supply Chain Network

Economic circulation and sustainable e-waste treatment both depend on supply chain consideration. Supply chain networks consist of two primary components: the governmental and unauthorised. It has been reported that the informal one is small. It needs to implement technology more efficiently in the conveyance of goods and services. This process is time-consuming, labour-intensive, and is mostly unregulated.[13] Sustainable management is challenging because of inappropriate management practices, including acid leaching, disassembly, and improper landfilling, whereas the adoption of formal recycling is hindered by their prevalence and presence. The management, segregation, and dismantling of e-waste are all made more challenging by the variety of its components (Fig. 2). Although EPR (Extended Producers' Responsibility) is thought to be the most practical strategy, its implementation framework is inadequate. The Analytical Hierarchy Process and Quality Function Deployment for decision-making, assessments, and system management may both be used to manage e-waste. Utilizing both structures will increase the supply chain network's effectiveness by helping to govern the predefined important elements. This model is used to handle the largest e-generator handling systems, demonstrating the importance of this procedure (Fig. 3). Additionally, research found that each rise of $1,000 in GDP would result in a 0.5-kilogram increase in the production of e-waste. This unequivocally calls for dynamic and sustainable management.[14–16] The reuse and recycling of electronic garbage, or "e-waste," have grown in significance in today's technologically advanced society. Even while recycling e-waste saves resources and lessens the amount of hazardous trash dumped in landfills, it additionally causes health effects that need to be addressed.

Management of Electronic Waste

We live in a time of rapid technological progress. Smartphones have largely replaced traditional mobile phones, LED and LCDs have largely replaced televisions, and desktop computers have largely been replaced by laptops and tablets. When a new product model is released, the previous model becomes obsolete and is discarded.[17] In affluent nations like the US, UK, Japan, and South Korea, among others, hundreds of thousands of tonnes of electronic waste are generated annually. The cost of processing electronic waste is unaffordable in developed nations. Because shipbuilding is relatively cheap, waste is shipped to countries that are developing. In developing nations, labourers, factory owners, and locals can all indiscriminately salvage valuable goods from this waste material. They collect what is valuable and trash the remaining items. For

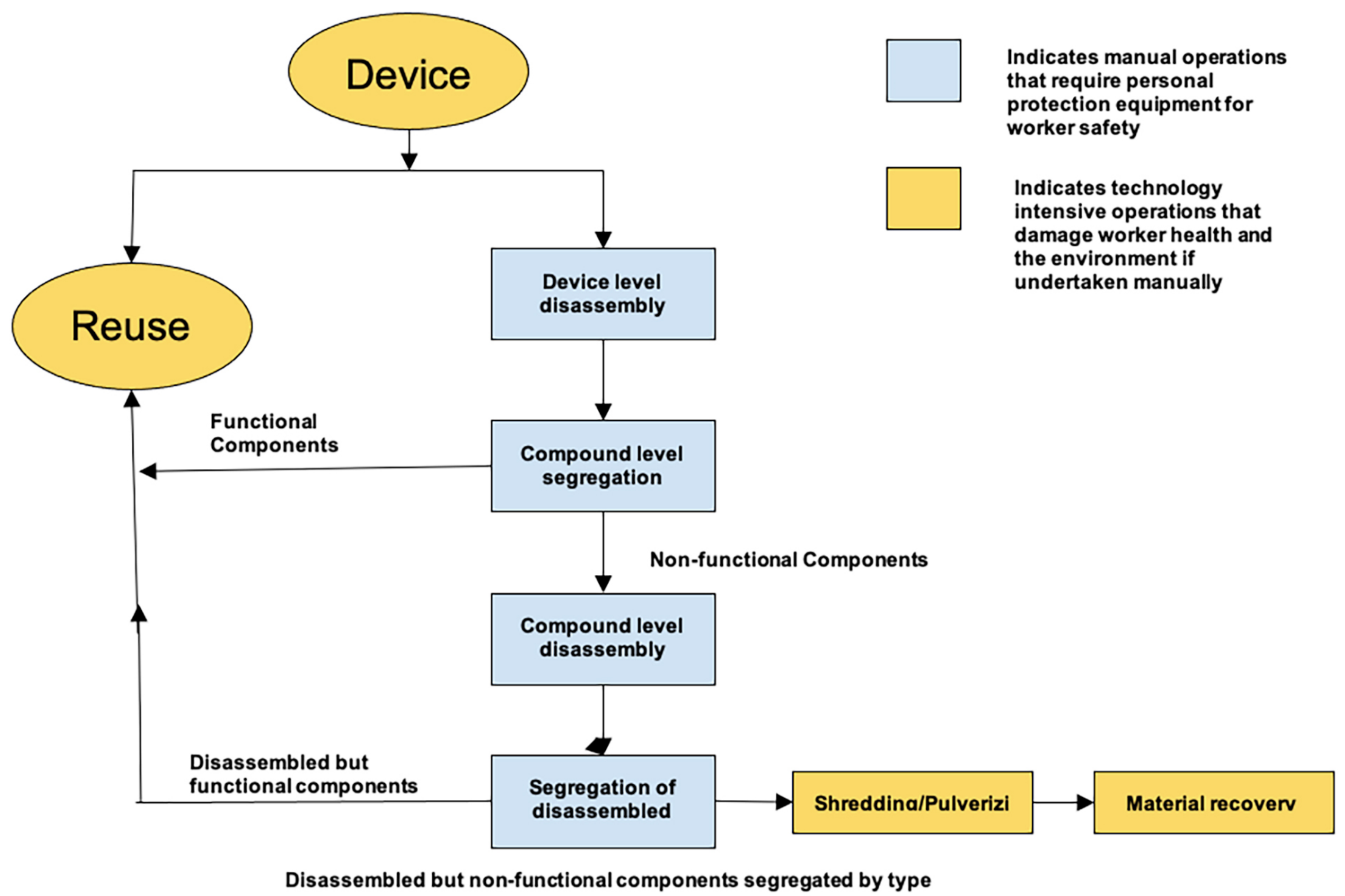

Figure 3. Various processes in e-waste recycling

the restoration of valuable chemical substances, acid baths and electronic burns are being used. Such approaches may be detrimental to people and have been associated with substantial health issues. India possesses urban e-waste processing centres that rapidly recycle raw electronic waste, particularly in cities like Chennai, Mumbai, and New Delhi. The capital city of India releases more than fifteen thousand tonnes of electronic garbage annually.[18] On the contrary, fourteen thousand tonnes of e-waste have been transported, primarily because of Chennai's immediate proximity to the port. Roughly 19,000 tonnes of electronic waste were generated in the city of Mumbai in the year 2007. Dioxin-like PCB compounds are widespread in the Indian atmosphere, which is an indication of the shipbreaking and e-waste shredding operations carried out in Mumbai's large industrial sector.[18]

Dangerous Recycling Operation

Several extremely harmful compounds, such as heavy metals like lead (Pb), mercury (Hg), arsenic (As), copper (Cu), cadmium (Cd), nickel (Ni), zinc (Zn), gold (Au), silver (Ag), and beryllium (Be); persistent organic pollutants (POP), such as polychlorinated biphenyls (PCBs) and polycyclic aromatic hydrocarbons (PAHs); polybrominated diphenyl ethers (PBDEs); and polychlorinated dibenzo-p-dioxins and dibenzofurans (PCDDs/Fs), are reported to be emitted or formed during the recycling process of e-waste. The environment, humans, and animals are all harmed by the toxic chemicals released by these pollutants.[19] Combustion of electric wires and printed circuit boards and heat treatment of polymer products are suspected to be the sources for high PCBs in e-waste sites of India, especially the most toxic, PCB-126.[18] Open burning, disassembly, incineration, ash washing, acid baths, and other practices are activities that are part of informal e-waste recycling, which emits numerous toxic or dangerous substances, including brominated flame retardants (BFRs), chlorine, neurotoxins, heavy metals (Cd, Cu, Ni, Pb, and Zn), volatile nitrogen compounds, and persistent organic pollutants (POP).[20] People exposed to these dangerous substances are impacted by recycling, including those who suffer acute lung damage from breathing in heavy metal fumes. Fine particulate matter from combustion results in cardiovascular and pulmonary illnesses.[21]

Impact of E-Waste Recycling

Workplace dangers

Electronic device disassembly and processing are required for e-waste recycling, which exposes employees to several occupational risks. Some of these dangers consist of:

Exposure to toxic chemicals

Hazardous compounds may be exposed as a consequence of improper handling and insufficient safety precautions, which can cause neurological illnesses, skin disorders, and respiratory difficulties.[22]

Exposure to particulate matter

The breaking down and burning of electronic parts may release particles into the air that, when breathed in, can aggravate respiratory conditions like coughing and wheezing and harm the lungs. Due to the laborious dismantling of electrical equipment, workers in e-waste recycling may potentially suffer bodily accidents, including cuts, burns, and injuries to their muscles.[23]

Pollution of the environment

Recycling e-waste has a negative influence on the environment and the neighbouring populations' health in addition to that of the employees. Inadequate recycling and disposal procedures may contaminate agricultural land and groundwater by leaching heavy metals and other hazardous compounds into the soil. These dangerous compounds may enter the body via the consumption of crops produced in polluted soil.[24]

Water pollution

Incorrect disposal or recycling may result in the discharge of poisons into water bodies, harming aquatic ecosystems and potentially compromising supplies of drinking water. This can lead to numerous health issues, including organ damage and gastrointestinal problems.[25]

Unofficial recycling methods

Reprocessing electronic waste is often done informally by marginalized groups in many poor nations, putting such people at serious health risk. These unregulated informal practices sometimes entail consuming e-waste to retrieve valuable components, which introduces dangerous toxins into the atmosphere. Due to extensive exposure to harmful chemicals, these populations are more likely to develop respiratory illnesses, skin ailments, and other health problems.[26]

Risks to Vulnerable Populations' Health

Children and pregnant women are two groups more susceptible to the negative effects of recycling e-waste on their health. Due to exposure to pollutants, children who live close to informal recycling facilities may have developmental delays and cognitive disabilities. Proximity to electronic waste contaminants during pregnancy could raise the likelihood of negative pregnancy outcomes.[27]

Reliable Recycling Methods

Concerns about the health effects of recycling e-waste are being addressed. Health risks may be considerably reduced by the use of responsible recycling techniques, such as the use of protective equipment for employees, suitable ventilation, and the application of safety laws.[28]

DISCUSSION

According to the study conducted by Chaturvedi et al.,[29] in India, the majority of electronic waste recycling is mainly done on an informal basis. Just 5% of all e-waste is appropriately collected and recycled, with the unorganized sector handling 95% of this. There have been 4.5 lakh child laborers between the ages of 10 and 14 who have been involved in the collection and processing of e-waste. Without safety precautions, extended exposure to these discarded e-wastes during recycling causes serious harm to brain development, heart function, lung cancer, the nervous system, respiratory syndromes, and skin conditions. In 2018, India's yearly e-waste processing capacity was 4.56 times smaller than its share of e-waste generation (Fig. 4). Lack of infrastructure for recycling and ignorance of the proper disposal process are the main causes of the rising value of e-waste, according to Rajesh et al.[30].

The health of recycling employees and the environment at large may be negatively impacted by the current management practices in India, according to observations. The recycling operations that are conducted present a complete risk. Urban poor individuals typically use methods like acid bathing to remove valuable and reusable components from electronic waste without considering any safeguards for their personal safety or health. Moreover, the challenge of recycling electronic waste in the entire country is made worse by the active engagement of children and women in these types of programs. Businesses that recycle e-waste in India pres-

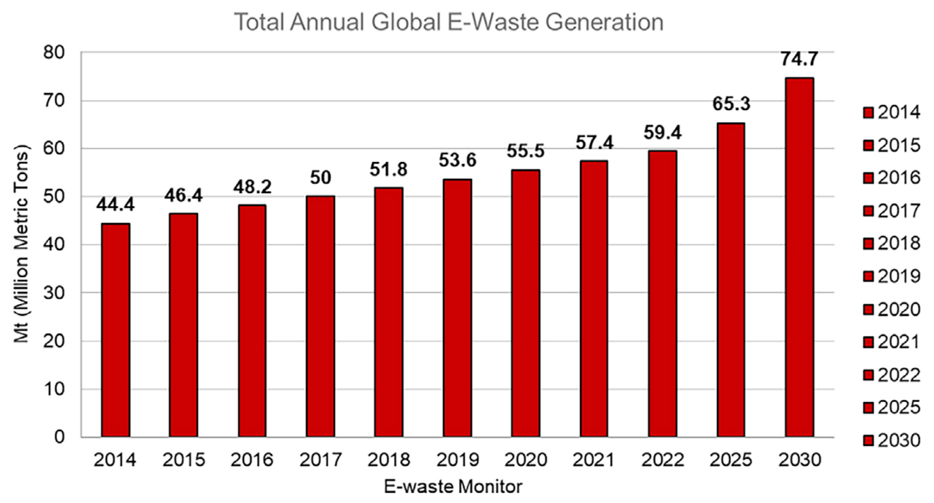

Figure 4. E-waste generation total annual global[30]

ent major risks to both the environment and the health of the people who work there. Numerous studies have demonstrated that the health of those who live close to the e-waste recycling plants is negatively impacted, in addition to the individuals who perform the recycling operation. One of the main issues in India is that the majority of those working in the recycling industry are poor and illiterate; thus, they are completely ignorant of the risks that recycling e-waste poses to both the environment and human health. Such recycling locations may result in uncontrolled pollution of the soil, air, and water, and this pollution, however, is neither tracked nor measured, according to Wath et al.[31].

India's whole electronic waste management framework is labour-intensive, and the majority of the recovering and recycling activities are performed using obsolete technologies and procedures, which might end up in the discharge of uncontrolled harmful substances. A comprehensive examination of the chemical risks related to the treatment of e-waste was carried out by Tsydenova and Bengtsson.[32] According to the report by Sthiannopkao et al.,[1] many different kinds of toxins are released into the workplace and environment as a consequence of unregulated recycling activities. The authors also note that in nations like China and India, the sheer quantity of e-waste generated, along with the crude recycling methods, is already having a negative impact on the environment and the general population. Metals from e-waste, for instance, are dissolved in strong acid solutions in these major countries and then extracted. In a similar way, a study conducted by Kaliyavaradhan et al.[3] found that electronic waste is hand-cleaned of plastic before being mechanically shredded. Besides that, it is widespread in developing nations to burn waste and unwanted scrap in the open. Such activities operate without exercising any necessary measures concerning the safety and well-being of the employees. Additionally, the workers and the residents are subjected to the toxins via their food intake, skin contact, dust consumption, and inhalation.

CONCLUSION

Unprecedented levels of ease, communication, and invention have been brought about by the digital era. E-waste, or electronic garbage, is a severe burden that mankind must now face as a result of this amazing transition. This in-depth analysis has looked at the many adverse consequences that e-waste has on the environment and public health, creating a narrative that emphasises the pressing necessity for responsible and sustainable e-waste disposal.

E-waste significantly contributes to soil, air, and water contamination. When electronic gadgets are inappropriately disposed of in landfills, their hazardous and precious metal-filled interiors contaminate the soil and groundwater. Brominated flame retardants, cadmium, lead, and mercury are simply a handful of the poisons that invade ecosystems and endanger animals and human populations by entering the food chain. Furthermore, energy-intensive e-waste disposal procedures like recycling and cremation emit greenhouse gases, accelerating climate change. The hazardous impact of e-waste on the environment is a serious issue that cannot be disregarded.

E-waste poses serious and well-documented risks to human health. Direct contact with the harmful materials present in electronic gadgets may cause a variety of health concerns, including cancer, neurological diseases, respiratory troubles, and developmental abnormalities. Informal e-waste workers in underdeveloped nations are especially at risk because they often lack protective gear and knowledge of the dangers they confront. The interconnectedness of e-waste's health consequences emphasises how urgent it is to solve this hidden danger to the public. Healthful waste is a global issue that cuts across national boundaries and requires shared accountability.

International laws and programs like the Basel Convention and the Waste Electrical and Electronic Equipment Directive show that the issue of e-waste is understood to be a global one. However, strict enforcement and international collaboration are necessary for these restrictions to be successful. The ethical aspect of e-waste also emphasizes the need for a fundamental change in consumer behaviour and business practices. Sustainable e-waste disposal methods that take into account the complete lifespan of electronic equipment are the way ahead. Principles of the circular economy, extended producer responsibility, and eco-design provide potential ways to limit the production of electronic trash, encourage responsible disposal, and encourage recycling.

Innovation and technology are essential, with improvements in material recovery, safe dismantling methods, and e-waste monitoring systems having the potential to completely change the industry. In conclusion, the damage that electronic waste does to the environment and human health is a complex situation that has to be addressed right now. A comprehensive strategy for managing e-waste is necessary due to the interdependence of these effects. To enforce strict legislation, encourage conscientious usage, and improve enduring e-waste disposal practices, governments, industry, and consumers must work together. To promote a culture of ethical electronic use and disposal, education and awareness are equally important.

The e-waste problem is a symbol of modern consumer culture and technological advancement. Effective management requires coordinated efforts among government, industries, and consumers to take urgent action toward a more responsible and ethical approach to the use and disposal of electronic devices to preserve the environment, protect public health, and secure a sustainable future. A coordinated, multi-sectoral approach can reduce environmental and health risks caused by electronic waste and guarantee a more ecologically sound, healthy planet for generations to come.

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