International Journal of Research Publication and Reviews

Journal homepage: www.ijrpr.com ISSN 2582-7421

A Global Perspective on Current Scenario and Future Scope of E-Waste in Developing Countries

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ABSTRACT—

The fraction including iron, copper, aluminium, gold and other metals in e-waste is over 60%, while pollutants comprise 2.70%. Given the high toxicity of these pollutants especially when burned or recycled in uncontrolled environments, the Basel Convention has identified e-waste as hazardous, and developed a framework for controls on transbound arymovement of such waste. The Basel Ban, an amendment to the Basel Convention that has not yet come into force, would go one step further by prohibiting the export of e-waste from developed toindustrializing countries what it is composed of and which methods can be applied to estimate the quantity of e-waste generated. Considering only PCs in use, by one estimate, at least 100 million PCs became obsolete in The increasing rate of WEEE production and its hazardous contents raise the concern regarding e-waste. This paper describes the research development on e-waste and proposes the perspective of future research. The study based on the literature survey in open access articles using 'e-waste' as the keyword. Article selection was done by considering the reputability of the source and cited frequency. From the articles reviewed, China contributed to most of the researches. Some of the most studied topics, namely management of e-waste, environmental and human health effects, and current status of e-waste treatment in a specific region. A brief explanation of each topic and insight on future research are also provided.

1. Introduction

The exponential growth of technology in recent decades has led to a surge in electronic device production and consumption worldwide. While these devices have undoubtedly improved our lives, they also present a looming environmental and health challenge: electronic waste, or e-waste. This global phenomenon encompasses discarded electronic equipment, including smartphones, laptops, televisions, and more. Developing countries, in particular, find themselves at the forefront of this mounting crisis. This discussion explores the current scenario and the future scope of e-waste in developing nations, shedding light on the complex issues and potential solutions that lie ahead.

As of the last knowledge update in September 2021, e-waste in developing countries had reached critical proportions, driven by factors such as rapid technological advancement, increased consumerism, and the global dissemination of electronic devices. Developing countries, often lacking adequate infrastructure for e-waste management, faced unique challenges in handling this electronic detritus. Informal recycling sectors, operating without proper regulations or protective measures, were prevalent, exacerbating environmental degradation and endangering the health of workers and nearby communities.

This exploration delves into the current scenario by examining the proliferation of e-waste, the informal recycling sector's prevalence, the associated environmental and health hazards, and the regulatory efforts made by some developing nations to address these issues.

Furthermore, we contemplate the future scope of e-waste in these countries. With technology continuing its rapid expansion, e-waste generation is expected to soar. This discussion envisions a future where developing nations make strides in building robust e-waste management infrastructure, fostering circular economy initiatives, participating in international cooperation agreements, and promoting sustainable technology development. These developments could not only mitigate the adverse effects of e-waste but also generate economic opportunities and contribute to the global effort to combat this pressing concern.

In summary, this exploration provides a comprehensive overview of the current scenario and future prospects of e-waste in developing countries, highlighting the need for proactive measures to address the mounting challenges while harnessing the potential benefits of responsible e-waste management.

The fraction including iron, copper, aluminium, gold and other metals in e-waste is over 60%, while pollutants comprise 2.70%. Given the high toxicity of these pollutants especially when burned or recycled in uncontrolled environments, the Basel Convention has identified e-waste as hazardous, and developed a framework for controls on transbound arymovement of such waste. The Basel Ban, an amendment to the Basel Convention that has not yet come into force, would go one step further by prohibiting the export of e-waste from developed toindustrializing countries what it is composed of and which methods can be applied to estimate the quantity of e-waste generated. Considering only PCs in use, by one estimate, at least 100 million PCs became obsolete in The increasing rate of WEEE production and its hazardous contents raise the concern regarding e-waste. This paper describes the research development on e-waste and proposes the perspective of future research. The study based on the literature survey in open access articles using 'e-waste' as the keyword. Article selection was done by considering the reputability of the source and cited frequency. From the articles reviewed, China contributed to most of the researches. Some of the most studied topics, namely management of e-waste, environmental and human health effects, and current status of e-waste treatment in a specific region. A brief explanation of each topic and insight on future research are also provided.

2 Current Scenario

2.1 Increasing E-Waste Generation

E-waste, which includes discarded electronic devices like smartphones, laptops, and televisions, has been growing at an alarming rate worldwide, with developing countries contributing significantly to this increase. The proliferation of electronic devices and shorter product lifespans are key drivers of this growth. This year's Waste Electrical and Electronic Equipment (WEEE) will total about 57.4 million tonnes (MT) and will be greater than the weight of the Great Wall of China, Earth's heaviest artificial object**.**

According to the Central Pollution Control Board (CPCB), India generated more than 10 lakh tonnes of e-waste in 2019-20, an increase from 7 lakh tonnes in 2017-18. Against this, the e-waste dismantling capacity has not been increased from 7.82 lakh tonnes since 2017-18.The major problem associated with e-waste management is its ever increasing quantum. However, the e-waste quantities represent a small percentage of the overall municipal solid waste (MSW). Data on e-waste generation may vary between areas of a country because of the definitions of waste arising, technological equipment used, the consumption patterns of the consumers, and changes in the living standards across the globe . Global e-waste generated per year amounts to approximately 20-25 million tons, most of which is being produced in rich nations such as the United States (US) or European Union member countries. The US, is the largest generator of e-waste, with a total accumulation of 3 million tons per year; and China is the second largest, producing 2.3 million tons each year. Brazil generates the second greatest quantity of e-waste among emerging countries

In Malaysia, the volume of e-waste generated is estimated at roughly 0.8-1.3 kg of waste per capital per day, with an increasing trend of e-waste generation, which rose to 134,000 tons in 2009. Furthermore, the volume of e-waste in Malaysia is expected to rise to 1.1 million metric tons in 2020, at an annual rate of 14% In South Africa and China, e-waste production from old computers will increase by 200-400% from 2007 to 2020, and by 500% in India. In this same period e-waste from televisions will be 1.5-2 times higher in China and India; whereas in India, e-waste from discarded refrigerators will double or triple by 2020. For India, the volume of e-waste generated is 146,000 tonnes per year. However, these data only include e-waste generated nationally and do not include waste imports (both legal and illegal) which are substantial in emerging economies such as India and China . The reason is that large amount of WEEE enters India from foreign countries without paying any duty in the name of charity . The rate at which the e-waste volume is increasing globally is 5 to 10% yearly

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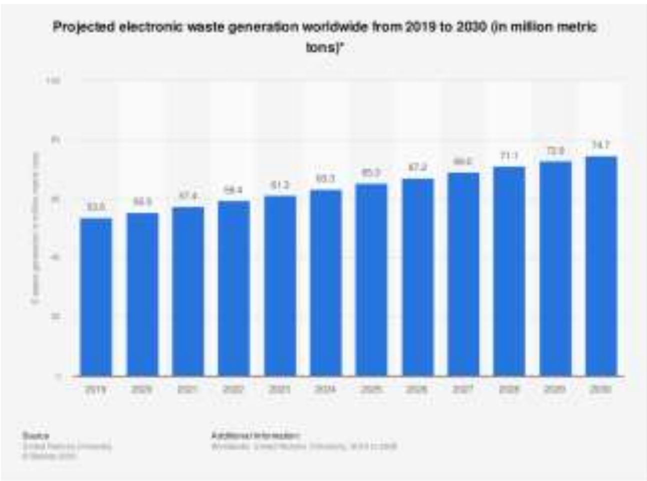


Fig.1 increasing E-Waste Generation Diagram

2.2 Informal Recycling Sector:

Many developing countries lack proper e-waste management infrastructure. As a result, a substantial portion of e-waste ends up in the informal recycling sector, where workers, often without adequate protective measures, extract valuable materials from electronic waste. This informal recycling poses environmental and health risks Informal recycles typically collect discarded electronic devices and equipment from various sources, including households, businesses, waste dumps, and electronic waste collection centers. They may purchase or receive these items for free, depending on local practices. Upon collection, informal recyclers manually sort and segregate e-waste items. They categorize them based on the type of electronic device and the materials they contain, such as metals, plastics, circuit boards, and cables.Dismantling: Informal recyclers often dismantle electronic devices to extract valuable components and materials. This process may involve removing batteries, wires, memory chips, and other parts that can be resold or recycled.

Valuable materials, such as copper, aluminum, gold, and silver, are recovered during the dismantling process. These materials can be sold to local scrap dealers or processors for income.Informal recyclers sometimes identify and refurbish electronic devices that are still functional. These devices can be resold in local markets, contributing to the circular economy and reducing e-waste In formal recyclers often face challenges when disposing of non-recyclable or hazardous e-waste components, as proper disposal facilities may be lacking. This can lead to environmental contamination if not managed correctly.The informal e-waste management sector poses significant environmental and health risks due to the handling of toxic materials without proper safety measures. Workers and surrounding communities can be exposed to harmful substances.Workers in the informal e-waste sector often operate in the informal economy, which means they may lack job security, social benefits, and legal protections.

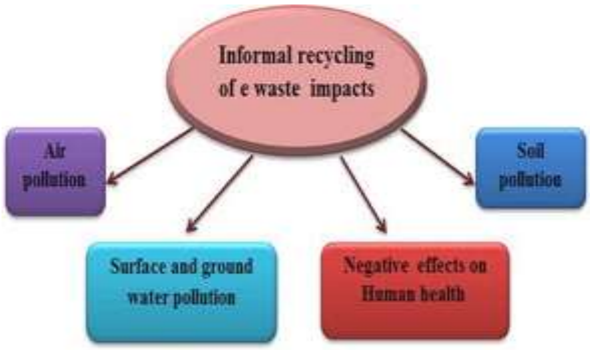


Fig. 2 Informal Recycling Sector Diagram

2.3 Environmental and Health Concerns

Inadequate disposal and recycling of e-waste lead to soil and water contamination due to the release of hazardous substances like lead, mercury, and cadmium. Additionally, the health of informal recyclers and nearby communities can be severely affected by exposure to toxic materials Many electronic devices contain hazardous substances such as lead, mercury, cadmium, brominated flame retardants, and polyvinyl chloride (PVC). When not properly managed, these substances can leach into the environment, contaminating soil and water. E-waste components can release toxic chemicals when they break down in landfills. These substances can infiltrate the soil, making it unsuitable for agriculture or other land uses. Hazardous materials from e-waste can also contaminate groundwater and surface water. This pollution can affect aquatic ecosystems, harm wildlife, and jeopardize access to safe drinking water. The burning of e-waste in open-air settings, a common practice in informal recycling sectors, releases toxic fumes and particulate matter into the air. This air pollution can have adverse effects on human health and the environment.Resource Depletion: E-waste contains valuable resources such as rare metals (e.g., gold, silver, and palladium) and high-quality plastics. When not properly recycled, these resources go to waste, contributing to resource depletion and the need for more resource extraction.

Health Concerns:

Informal e-waste recyclers, who often lack protective gear and work in unregulated conditions, are at risk of direct exposure to hazardous materials. This exposure can lead to acute and chronic health problems, including respiratory issues, skin disorders, and neurological disorders. E-waste recycling activities conducted in close proximity to communities can expose residents to toxic substances through air, water, and soil contamination. This can result in adverse health effects for nearby populations, including children. Hazards: Improper disposal of e-waste in landfills or incineration facilities can lead to fires and the release of toxic chemicals, further endangering the environment and public health. Exposure to hazardous substances from e-waste can have long-term health consequences, with potential impacts on neurological development, reproductive health, and cancer risk.

3 Future Scope

3.1 Rising E-Waste Volumes

E-waste generation is expected to continue growing as technology becomes more pervasive in developing countries. The rapid adoption of smartphones, tablets, and other electronic devices will contribute to this trendTechnological Advancements: The rapid pace of technological innovation leads to the frequent release of new electronic products with improved features and capabilities. As consumers desire the latest technology, older devices become obsolete, contributing to e-waste.Modern consumer culture encourages the frequent replacement of electronic devices with newer models, even if the existing devices are still functional. This consumer behavior drives the disposal of perfectly usable electronics. Many electronic products, particularly consumer electronics, are designed with relatively short lifespans. This planned obsolescence strategy prompts consumers to replace their devices more frequently The world's increasing population means more people are using electronic devices, leading to a higher overall volume of e-waest Developing countries are experiencing economic growth, resulting in greater access to electronic devices. This contributes to increased e-waste generation in regions with emerging economies.Technological advancements often render older devices incompatible with newer software or hardware, compelling consumers to upgrade to the latest models. Emerging trends such as the Internet of Things (IoT), smart homes, and wearable technology introduce a wide array of electronic devices, further accelerating e-waste generation

Improper disposal and recycling of e-waste can lead to environmental contamination, as electronic devices often contain hazardous materials like lead, mercury, cadmium, and brominated flame retardants. E-waste contains valuable resources like metals (e.g., gold, silver, and copper) and high-quality plastics. Failing to recover and recycle these resources contributes to resource depletion. Inadequate handling and disposal of e-waste can expose workers and nearby communities to hazardous materials, posing health risks such as respiratory issues and skin disorders.Managing the increasing volume of e-waste is a complex logistical and regulatory challenge, requiring robust recycling infrastructure and proper disposal methods.

3.1 E-Waste Management Infrastructure

Developing countries are likely to invest in building and improving e-waste management infrastructure. This includes establishing collection centers, recycling facilities, and educational programs to promote responsible disposal among consumers.E-waste recycles in India is predominantly an informal sector activity. There are thousands of poor households eking a living from scavenging materials from waste dumps. The common recycling practices for middle-class urban households, particularly for waste paper, plastic, clothing, or metal, is to sell out to small-scale, informal sector buyers often known as ‘kabadiwalas,’ and they further sort and sell these as an input material to artisanal or industrial processors.E-waste management in India follows a similar pattern. An informal e-waste recycling sector employs thousands of households in urban areas to collect, sort, repair, refurbish, and dismantle disused electrical and electronic products. However, there is a different situation in advanced countries, and there is no concept in India of consumers voluntarily donating the useless electrical and electronic equipment at formal e-waste recycling centers. Also, there is not a concept of consumers paying for disposal of the e-waste they generate.

Fig.3 **E**-Waste Management Infrastructure

3.2. Circular Economy Initiatives:

There's growing interest in adopting circular economy principles, which focus on recycling, refurbishing, and extending the lifespan of electronic products. This approach could reduce the overall e-waste burden and create opportunities for local businesses Circular economy (CE) is an industrial system that is restorative or regenerative by intention and design.It replaces the end-of-life concept with restoration and regeneration, shifts towards the use ofrenewable energy, eliminates the use of toxic chemicals, which impair reuse and return to the biosphere, and aims for the elimination of waste through the superior design of materials, products,systems, and business models. It serves as an alternative to current model of highly extractive and resource-intensive linear economy, and aims at maintaining and retaining value of resources, produc tsand materials at their highest by keeping them in use as long as possible.

It also aims at minimizingwastage at each life-cycle stage, and extracting the maximum value through reusing, repairing,recovering, remanufacturing and regenerating products and materials at the end of each service value.A transition towards CE will serve to reduce dependency on virgin materials and enhance resourceproductivity. As India recovers from the COVID-19 impacts especially on society and economy,selfreliance or Atmanirbhar Bharat becomes crucial to address these challenges and recover backthrough sustainable growth models. The Indian recovery strategies need to sustainably promoteconditions to rebuild for people, environment, and economy. This would necessitate increasedinvestment in skills, sectors, products, business models, processes, digitalization and technologies thatcan create long term prosperity for humankind and a healthy planet.

3.4 International Cooperation:

As e-waste is a global issue, international cooperation and agreements, such as the Basel Convention, are crucial for managing cross-border e-waste flows. Developing countries are likely to participate more actively in such initiatives to mitigate e-waste-related challenges. In 2016, only about 20 percent of all e-waste globally was recycled. Certain components of electronic products contain materials that are hazardous when not disposed of correctly and can leach lead and other substances into soil and groundwater. Many of these products can be reused, refurbished, or recycled in an environmentally sound manner so that they are less harmful to the ecosystem and reduce the need to extract or manufacture virgin materials to fabricate new products.The United States Environmental Protection Agency (U.S. EPA) and the Taiwan Environmental Protection Administration (Taiwan EPA) have collaborated through the International Environmental Partnership since 2011 to build global capacity for the environmentally sound management of waste electrical and electronic equipment (WEEE), which is commonly called e-waste. To support this goal, U.S. EPA and Taiwan EPA coordinate the

3.5 Sustainable Technology Development:

There's potential for developing countries to adopt more sustainable technology practices. This could involve designing products with longer lifespans, easier repairability, and reduced environmental impact.Electronic waste (e-waste) refers to broken down electronic devices that are no longer useful for the purposes they were intended for (Luther, 2009). The definition includes Electrical or Electronic Equipment's (EEE) that use electric power but have reached their end-of-life. Other components of e-waste such as power cables, sub assemblages and consumables that are part of electronic products at the time of discarding them are part of the waste (European Union, 2002; UNEP, 2007). The definition of e-waste includes electronic products that are not spoilt but discarded by their owners (UNU/Step, 2014).

Electronic waste is not just waste in the real sense, but a great business opportunity for those engaged in the selling and recycling of the waste. As a result, large inflow of Electronic waste into developing countries has occurred due to weak regulatory standards and poor enforcement of environmental laws when it comes to extraction and handling of valuable metals such as silver, gold and iron from e-waste (Chatterjee, 2012). In essence, African countries such as Kenya was considered the highest importer of electronic waste in 2010 when it imported, 1,400 tons of refrigerators, 2,800 tons of TV sets, 2,500 tons of personal computers, 500

Table 1: Comparisons of E-waste Management Strategies and Techniques

S/No	Strategies	Features	Applications
1	Life Cycle Assessment (LCA)	Material consumption estimation, Eco-design and development, Environmental aspects evaluation, Economic evaluation, Decision making, Life disposal of electronic devices	Recycling of computers, mobile phones, notebook computers, Decision maker, Treatment scenario, Recycling systems
2	Material Flow Analysis (MFA)	E-waste generation investigation, E-waste estimation, Decision making	E-waste flow, Trade value chain, Flow of used computers, E-waste quantities
3	Multi Criteria Analysis (MCA)	Decision making, Provide environmental evaluation	Decision making, E-waste management decision systems, Location evaluation
4	Extended Producer Responsibility (EPR)	E-waste problems solutions, Polluter-pays principle based enforce producers	Flow systems, Decision making
5	Reverse Logistics	Control flow of e-waste, Enhance flow process, Improve economic values	Flow system, Decision making, Flow control

Table 1. Sustainable Technology Development

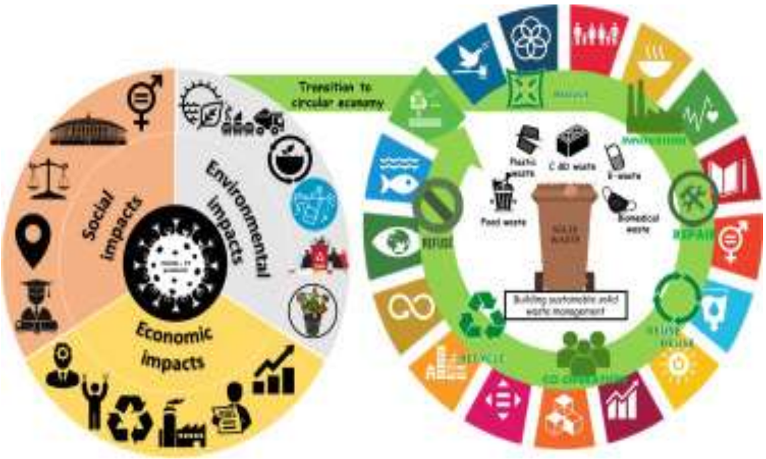
3.5 Economic Opportunities:

The economic growth of emerging and frontier economies has created several global challenges; one of these challenges is related to the resources not reused in industrial activities and a large amount of waste generated. Waste pollution is one of the most significant environmental issues in the modern world. The importance of recycling is well known, both for economic and ecological reasons, and the industry demands high efficiency (Majchrowska et al., 2022).

Therefore, identifying what developing countries need to address the challenges around resource efficiency and climate change is of great importance, understanding that these countries show a high preference for decreasing solid waste, emission reduction and energy-saving technology, solar energy, wind energy, and bioenergy (Tan et al., 2021).

Business models and regulatory frameworks tested and practiced in developed countries are not necessarily applicable to emerging market countries or frontier market countries due to the difference, not only in development stages but also in social, political, and cultural frameworks (Relva et al., 2021; Stadelmann and Castro, 2014). These countries need to identify optimal strategies that enable the utilization and reuse of materials, residues, and wastes that negatively impact the environment. Highlighting these opportunities and challenges is a significant step towards improving waste management performance, developing technologies, and implementing environmentally sustainable alternative solutions. The countries of the emerging and frontier economies have fundamental challenges related to the integral use of waste. These countries show significant increases in urbanization levels, and the production of municipal solid waste is expected to reach 3.4 billion tons per year by 2050 (Amaral et al., 2022). Implementing material reuse activities from an integral perspective allows these countries to develop industrially and socially without incurring the risks of depletion of natural resources.

Understanding behavioral patterns when dealing with Solid Waste Management (SWM) generates significant challenges at different levels of society. The industrial sector is no stranger to this reality, which is why the idea of creating environmental sustainability, maximizing resources, and achieving social, environmental, and economic benefits based on physical exchanges of waste and materials can become a reasonable business model for companies in emerging countries. Therefore, it is crucial to identify studies to improve waste processes in the business sectors to achieve sustainability.



3.4 Economic Opportunities

Conclusions

E-waste is an emerging issue, driven by the rapidly increasing quantities of complex end-of-life electronic equipment. The global level of production, consumption and recycling induces large flows of both toxic and valuable substances.The international regulations mainly developed under the Basel Convention, focusing on a global ban for transboundary movements of e-waste, seem to face difficulties in being implemented effectively; however, a conclusive account of the situation and trends is not The current scenario of e-waste in developing countries presents a pressing challenge, but it also offers opportunities for positive change. To address this issue, governments, industries, and civil society must collaborate to implement effective e-waste management strategies. The future scope involves the development of robust regulations, infrastructure investment, and public awareness campaigns. It is crucial to transition towards a circular economy and engage in international cooperation to create a sustainable and responsible approach to e-waste, safeguarding both the environment and the well-being of communities in developing countries. Failure to act may result in catastrophic consequences for the environment and human health, but with concerted efforts, we can mitigate the negative impacts of e-waste and pave the way for a more sustainable future.environmental issues, economic benefits, sustainable development, and competitive advances. This forces companies to put more effort to implement e-waste RSC practices to make them more effective. E-waste issues and the differences between forward and reverse supply chains have been discussed in this study. This paper then focuses on four main issues in e-waste RSC, including factors of implementation, performance evaluation and decision making, forecasting product returns, and network design. Published articles in this field have been selected and reviewed to identify the research gaps and suggest potential future research. The suggestions for future research direction would help researchers, policymakers, and practitioners to consider these topics in their work.

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