Review article

A comprehensive review on hazardous aspects and management strategies of electronic waste: Bangladesh perspectives

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HIGHLIGHTS

- Collection, recycling, and disposal processes have to be established in Bangladesh.
- E-waste generation in Bangladesh is 3.1 MMT including shipbreaking yards generation.
- Bangladesh has an e-waste business potential of 221 million USD/yr.
- The policies and legislations for e-waste management in Bangladesh are not adequate.
- A combined MFA and LCA model can help decision-making for e-waste management.

GRAPHICAL ABSTRACT
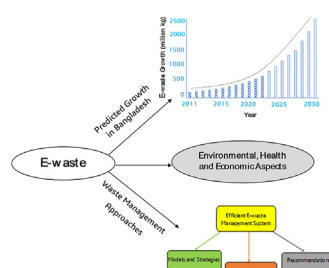
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ABSTRACT

Electronic waste (e-waste) contains a variety of electronic components e.g., metals, non-metals, plastics, cables, etc. The excessive generation of e-waste has become a significant concern in the last few decades. The current global e-waste generation is 57.4 million metric tons (MMT) per year. Asia produces the highest amount of e-waste (24.9 MMT) followed by America, Europe, Africa, and Oceania. In Bangladesh, e-waste produces from two sources: its own consumption of electronic devices, which is 0.6 MMT, and imported e-waste from ship breaking yards that is 2.5 MMT in 2021. However, inadequate information on the current state of e-waste generation and management systems in Bangladesh has created a void to establish the future direction for proper handling of e-waste. In this work, the Bangladesh perspective of e-waste has been analyzed. The environmental, health economical forfeiture of e-waste has been discussed. The development of government legislations regarding e-waste have been stated. The establishment of e-waste management has been designed by the life cycle assessment (LCA) and material flow analysis (MFA) models. Moreover, a holistic approach for understanding the possible hazards, the economic feasibility of e-waste processing and viable management models for e-waste in Bangladesh was endeavored in this work to propose systematic future directions and recommendations to improve the current e-waste scenario of Bangladesh.

1. Introduction

The technological innovation and advances, rapid industrial development, economic growth, and lifestyle have created huge demands for electronic devices such as television, mobiles, computers, hardware, AC, refrigerators, etc., and other electronic equipment for personal, office, and household application (Needhidasan et al., 2014). This high demand for electronic items generates a vast amount of electronic waste (e-waste) worldwide (Ismail and Hanafiah, 2020).

E-waste includes both hazardous and non-hazardous and precious components such as iron and steel (50%), other metals (13%), plastics (21%), glasses, and other substances such as ceramics materials, wood, and rubbers, etc. (16%) (Wath et al., 2011). Among other metals, platinum (Pt), gold (Au), cadmium (Cd), silver (Ag), palladium (Pd), zinc (Zn), lead (Pb), copper (Cu), cobalt (Co), nickel (Ni), and rare earth minerals e.g., yttrium (Y), lanthanum (La), cerium (Ce), neodymium (Nd) has been used in an increasing rate in electronic devices such as printed circuit boards (PCBs), computers, smartphones, television, printers, refrigerators, telecommunication servers, washing machines, photocopiers and coffee machines (Graedel and Lifset, 2016). The heavy metals like lead (Pb), nickel (Ni), cadmium (Cd), mercury (Hg), copper (Cu), and chromium (Cr), etc. and the halogenated organic constituents such as chlorofluorocarbons (CFCs), polychlorinated biphenyls (PCBs), polybrominated biphenyls (PBBs), brominated flame retardants (BFRs) present in e-waste are toxic to plant, human and aquatic living organisms (Song et al., 2013a; Graedel and Lifset, 2016). Therefore, improper handlings of e-waste results in the leaching and emissions of these toxic components in the soil, water, and air, which causes the death of certain aquatic plants and animals (Ankit et al., 2021). The uptake of these materials through plants, drinking water and direct inhaling can damage the human heart, kidney, brain, liver, birth capability and skeletal system (Kumar et al., 2017).

The recovery of metals is an efficient tool to unveil the monetary benefits of e-waste, which is an established practice in developed countries like USA, Japan, Taiwan, European Union (EU), and Canada (Ilyas et al., 2021b). The total e-waste handling process includes collection, recycling, and dumping stages (Tran and Salhofer, 2018). In developed countries, the collection of e-waste is controlled by authorized municipal or private organizations. In most cases, the waste is recycled in facilities with advanced technologies, apparatus, and infrastructure for the safe and effective removal of precious materials, and the rest of the unrecovered waste is disposed of following the proper guidelines (Perkins et al., 2014). The recycling business has huge market potential; however, it is not very sustainable due to the high workforce cost and utility cost of operating the e-waste recycling plant (Ilyas et al., 2022).

In contrast, in most developing and undeveloped countries, e-waste is collected in informal, scattered, and unauthorized ways by different companies, traders, or government bodies. The collected e-waste is either recycled or processed to extract valuable materials which are about 20% of total e-waste generation using rudimentary technology without adequate occupational safety precautions (Ahirwar and Tripathi, 2021). The rest of the e-waste is disposed of in landfills, which pollutes the environment by leaching into the soil and groundwater. Therefore, inefficient waste management strategies coupled with the excessive burden of e-waste have created social, environmental, and economic problems in developing countries of Asia like Bangladesh.

To the best of our knowledge, most of the published literature is mainly focused on the impacts of resources, policy, and legislation on materials recovery. Some articles reviewed metals' recovery process, including pyrometallurgy, physical and bio-hydrometallurgy methods. However, very few reviews demonstrated the overall e-waste generation associated with Bangladesh's hazardous aspects and management strategies. The country is now facing a severe problem due to the rapid growth of the e-products market because of the technological advancement and affordability of electronics devices (Yousuf and Reza, 2011). An inefficient e-waste management system in Bangladesh eventually adds up e-waste into the waste stream and affects various aspects of society (Debnath et al., 2018; Kaya, 2016; Yousuf and Reza, 2011). The country has not established a proper e-waste management system yet like other developing countries. The waste collection, disposal, and recycling are controlled by unauthorized sectors (Alam and Bahauddin, 2015).

Therefore, this article attempts to provide a comprehensive review of management strategies of e-waste in Bangladesh's perspective and comprises three phases. The first phase provides a detailed analysis of the past, present, and future state of e-waste generation globally and from Bangladesh's perspective. The second phase demonstrates the impact of socio-environmental, health, and economic opportunities of e-waste recycling, followed by different assessment methods and tools. The possible amount of precious metals recovery by e-waste recycling and its economic evaluation has also been reviewed. The development of legislation regarding e-waste in Bangladesh has been presented. Based on the literature, life cycle assessment (LCA) and material flow analysis (MFA) have become essential assessment models for quantifying various aspects of e-waste management systems and restoring metals into a circular economy. Finally, future directions and recommendations are made to manage e-waste to improve the situation efficiently.

2. Research methodology

The main focus of the study is to evaluate the types and amount of e-waste generation associated with potential management strategies. The adopted methodology was carried out for the review using steps to understand the topic in depth. In the first step, an extensive literature study was conducted to overview the exiting trend of e-waste generation at global and Bangladesh perspectives. The most recent articles from minor and major publishers (Scopus, Web of Science, Pub Med, Elsevier, Springer, Emerald, Google Scholar, and Wiley) were included in this database used as a complementary search engine. Several keywords such as e-waste generation, challenges, opportunities, waste management and strategies were chosen to avoid biased research. To achieve the stated objectives, primary and secondary data of e-waste has been collected from the highly cited and targeted published articles. The exploratory studies were demonstrated for understanding the gaps between the developed and developing countries. Based on this overall finding, the reports published at in Bangladesh, United States, United Kingdom, Malaysia, Vietnam, etc., were also reviewed. As a part of our literature search, the title and abstracts were checked to ensure the completeness of this review before choosing relevant papers. In the second step, the socio-environmental and health concerns associated with e-waste and the economic opportunities of e-waste recycling were investigated by assessment models. It has adverse effects on human health and the environment due to inappropriate handling, recycling, dismantling, and recovering of e-waste. In this approach, the objective was to know the awareness level of the workers about the impacts of e-waste and any health-related problems due to the handling of e-waste. Additionally, the assessment of each model was developed for increasing the performance of e-waste management and understanding the benefits of recycling.

During the whole process of the study, it was realized that Bangladesh has a limited database of recent e-waste generation associated with waste management. Hence, the overall review has focused to get an outlook on the scenario of e-waste in Bangladesh, the challenges, and opportunities associated with it.

3. Global scenario of e-waste generation

Electrical and Electronic Equipment (EEE) have been ingrained in modern living and lifestyles, and they come in a variety of shapes, sizes, functions, and degrees of sophistication. Size and weight, as well as functioning and composition, are used to classify EEE and, by extension, WEEE. Global e-waste monitoring in 2020 by United Nations (UN)'s stated that 53.6 million metric tons (MMT) of electronic waste (7.3 kg per capita) was generated worldwide in 2019 (excluding PV panels). About
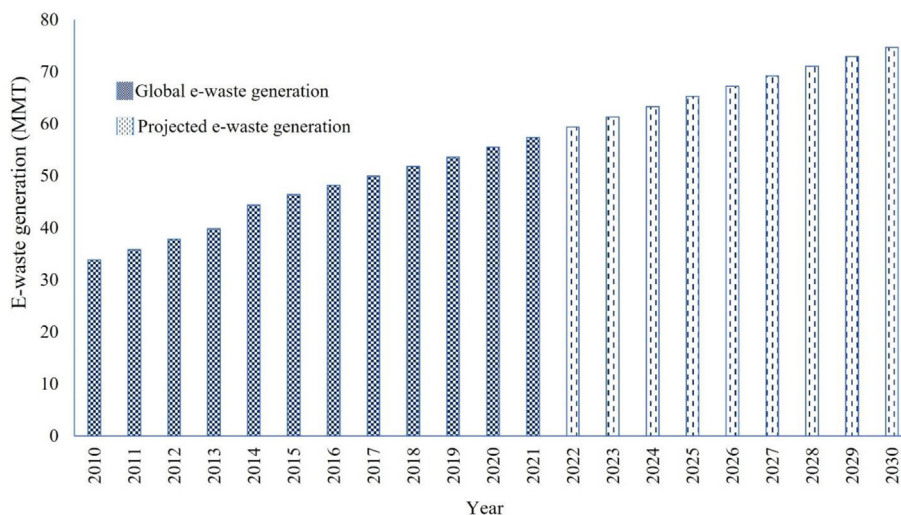
Figure 1. Global e-waste generation (year 2010 to 2019) and projected e-waste generation (year 2020 to 2030).
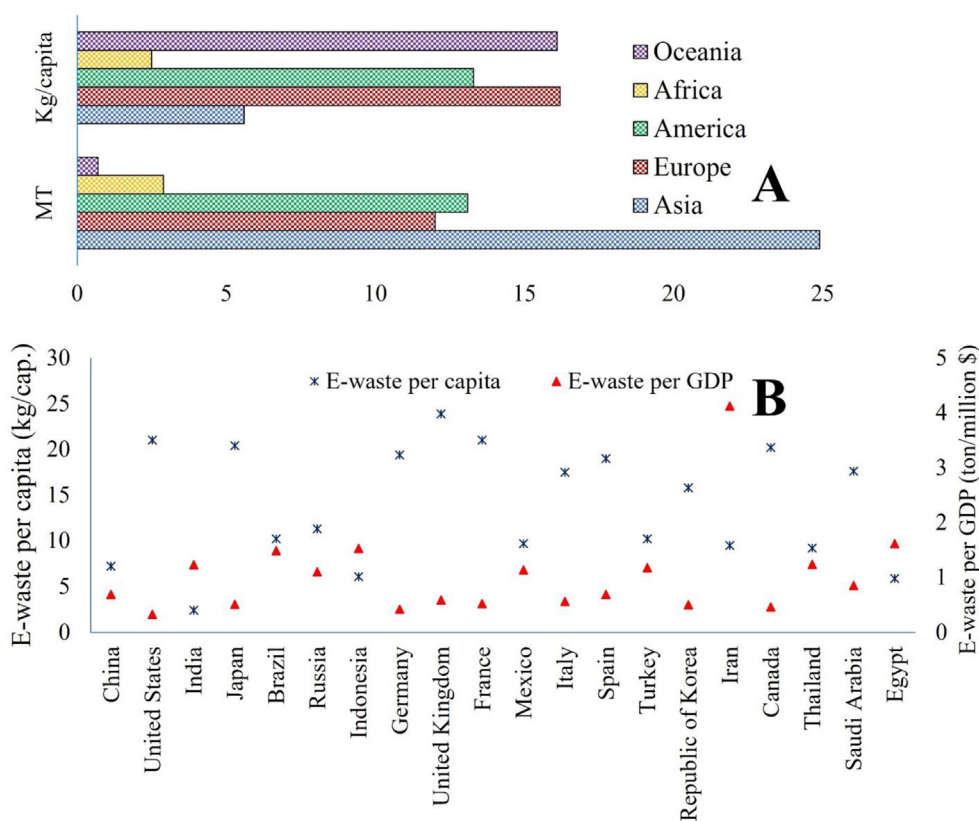

Figure 2. E-waste generation in the year 2019; A) by major Continents (Total and per capita basis) B) by major twenty Countries (per capita and per GDP basis).

21% rise of e-waste generated worldwide within the last 5 years is indicating the alarming situation currently (Ismail and Hanafiah, 2020). Each year about 2 MMT of extra e-waste is added to the previous e-waste generation globally from 2010 to 2020. In 2010, the global generation of e-waste was about 33.8 MMT, continuously rising every year, and in 2019 the quantity increased by 58% within ten years (Figure 1). However, in the upcoming ten years, the rate of e-waste generation is expected to rise remarkably, as shown in Figure 1. Nearly 121% (more than double) rise in e-waste quantity is expected worldwide from 2010 to 2030 (Forti et al., 2020). It is to mention that Forti et al. didn't consider the economic interruptions regarding the widespread Covid-19 situation.

Still, beyond any doubt, the alarming rate of e-waste generation has become one of the world's major problems. In 2021, the estimated e-waste generation was 57.4 MMT as published by WEEE, which was declared on international e-waste day 10 October 2021 in China, which converged the Forti et al. (2020) data (Figure 1).

Higher EEE consumption rates, short life cycles, and limited repair choices are all contributing to the increasing quantity of e-waste. In 2019, Asia produced the most e-waste (24.9 MMT), followed by the Americas (13.1 MMT) and Europe (12 MMT), with Africa and Oceania producing 2.9 MMT and 0.7 MMT, respectively (Figure 2A). As China is one of the most technologically sophisticated countries, it is evident that Asia has
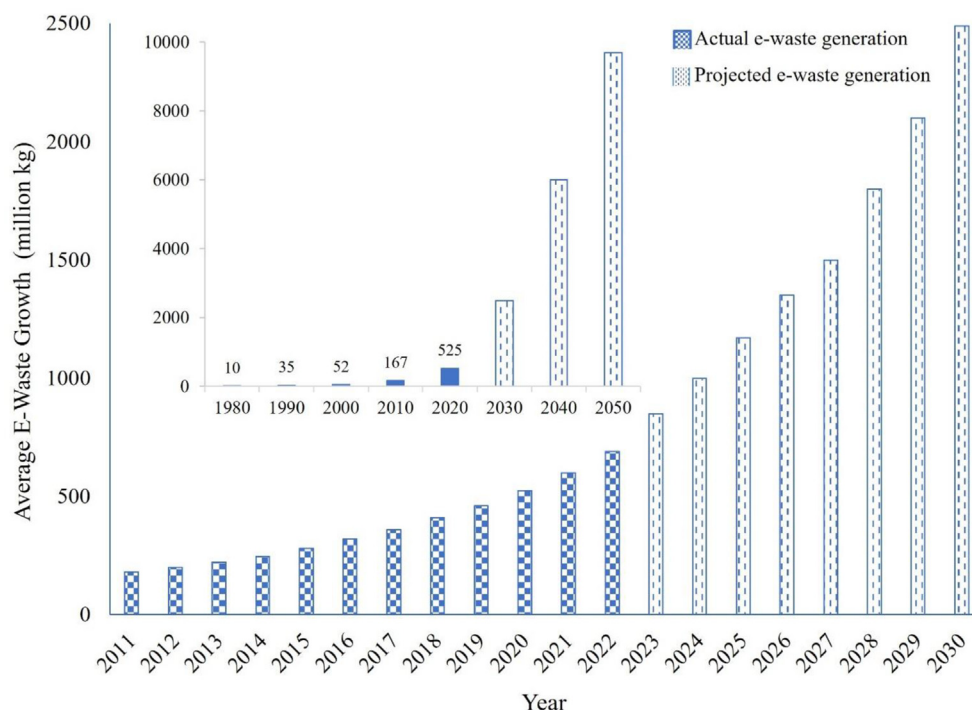
Figure 3. Bangladesh e-waste generation (year 1980 to 2021) and projected e-waste generation (year 2022 to 2050).

taken the lead in e-waste production. China manufactures a large number of electronic goods and, as a result, has the highest amount of e-waste (12 MMT). Furthermore, emerging Asian nations such as India, Bangladesh, and Pakistan, import e-waste for recycling, putting Asia in first place among all continents (Forti et al., 2020).

Moreover, with an average of 16.2 kg of e-waste per capita in 2019, Europe was the region that produced the highest e-waste (Figure 2A). This was somewhat higher than Oceania generated per capita (15.9 kg). America continents placed third in generating e-waste per capita (13 kg) followed by Asia (5.7 kg) and Africa (2.7 kg). Even though Europe has the most significant per capita rate, Asia generates the most overall e-waste because of the highest number of populations living in Asia (>50% of the world population). In larger GDP countries, greater economic prosperity leads to more EEE being placed on the market and, consequently, higher e-waste generation. Kusch et al. suggested that the relation between GDP and e-waste generation is not linear due to the saturation effect when moving from higher economic wealth to lesser economic wealth countries (Kusch and Hills, 2017). Figure 2B is illustrated to relate the major twenty country's e-waste generation per capita and GDP basis in 2019. All GDP data were retrieved from the official online database of the World Bank (Bank, 2019). In most European countries (i.e., Germany, Italy, France, United Kingdom, Spain), e-waste generation per capita was relatively higher (20–25 kg/capita) than in the other countries in 2019. However, based on GDP, their e-waste generation was not very significant at all (within 1 MT/million $). A similar trend can be seen in the case of United States e-waste generation. In Asian countries (India, Indonesia, Turkey, Egypt, etc.) e-waste generation per GDP was significantly higher (>1 MT/million$) with the exceptionally highest could be found in Iran (~4 MT/million$). Moreover, India got the lowest e-waste generation per capita basis (~2 kg/capita), probably due to its population density with respect to e-waste generation.

4. Bangladesh's perspective on e-waste generation

Many countries have a "not-in-my-backyard" mentality when it comes to the disposal of waste. There are loopholes in developing country rules that enable waste from developed nations to be exported. It is estimated
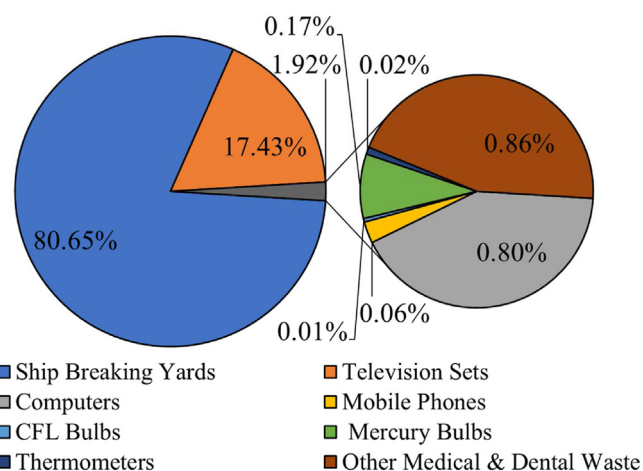

Figure 4. Percentage distribution of Bangladesh's e-waste generation sector.

that around 80 % of the world's electronic waste is sent for recycling and disposal in Asian and African countries. Moreover, European e-waste has been sent to Asian and African nations, especially Ghana, Nigeria and Bangladesh at a 40 percent rate (Alam and Bahauddin, 2015).

Due to Bangladesh's rapid technological advancement and economic growth over the last decade, the demand for mobiles, laptops, desktops, and other consumer electronic items has risen dramatically. Therefore, Bangladesh produces a significant amount of e-waste per year and most of those end up in landfills. Some electronic waste is recycled, dismantled for components, or discarded. This illegal practice is unsafe for both human and environmental health. However, imported electronic waste is now being disposed of by i) selling to the secondhand market at a reasonable price, ii) donating these items to various organizations, or iii) selling it for recycling to eco-friendly organizations. Even though it is regarded as the most viable, the final option is seldom used. Currently, the general public, government, and corporate sector are unaware of the e-waste problem. To understand the present state of e-waste management
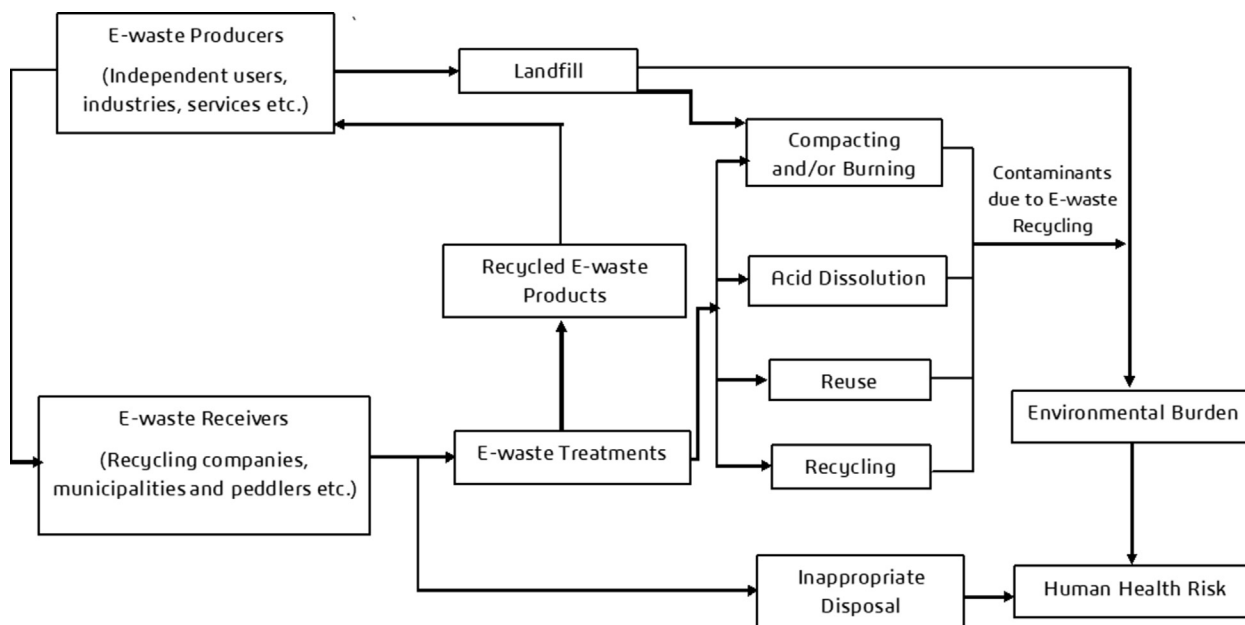
Figure 5. E-waste routes in the environment (Perkins et al., 2014).

in Bangladesh, a few research have been carried out (Ananno et al., 2021; Yousuf and Reza, 2011; Buet, 2018). Figure 3 depicts the substantial increase in electronic waste generation in Bangladesh over the last forty years. As of the year 2021, 600 million kg of e-waste was generated in Bangladesh. If current growth rates continue, this figure is predicted to climb to 10 billion kg by the year 2050. However, based on the previous year's growing trend, the predicted e-waste generation for the period 2022 to 2030 is shown in Figure 3. The figure depicts a more than fourfold increase in e-waste generation by 2030 when compared to the level of generation in 2020. According to Bangladesh's strong expansion in all areas, notably in the IT and mobile sectors, the predicted amount looks to be reliable.

Figure 4 shows the percentage distribution of Bangladesh's e-waste generation sector. The shipbreaking yards in Bangladesh are the primary source of e-waste, as seen in figure (80.65%). Bangladesh imports a huge number of scraps ships each year. In a shipbreaking yard, these vessels are being shattered into pieces. Many heavy metals and harmful contaminants, such as oil spills, are released into the environment during shipbreaking. E-waste vulnerability in Bangladesh is rising since Bangladesh has a legal obligation to import scrap ships, and hence illegal imports and trade-offs of e-waste are taking place by importers in order to gain money. Toxics and electrical and electronic garbage are being transported in massive quantities aboard the scrap ships (Esdo, 2011). Television sets account for 17.43% of all e-waste, followed by medical wastes at 0.86%, and computer accessories at 0.80% (Masud et al., 2019; Ananno et al., 2021; Ahirwar and Tripathi, 2021).

Bangladeshi authorities modified the first draft of the country's "e-waste management guidelines" in 2011, marking the country's almost 40-year anniversary of independence. The draft contains many pieces of law, such as shipbreaking regulations, the Environmental Conservation Act, medical waste management regulations, the Government 3R standards, and hazardous materials management regulations (Alam and Bahauddin, 2015). The government has also imposed several restrictions to maintain proper e-waste recycling, as e-waste recycling in a systematic way can be a profitable beneficial business model in developed as well as developing countries like Bangladesh (Garlapati, 2016). The annual business potential from e-waste in Bangladesh is approximately equivalent to 221 million USD (Parvez, 2020) against 7 billion USD in the world (Borthakur and Govind, 2017). In Bangladesh, the proper implementation of the environmental and health risk regulations for the workers associated with the different levels of e-waste management has not yet been

performed. The recycling of e-waste is controlled by the informal sectors and the ratio of recycling compared to the generation is very low. The unrecycled e-waste is therefore ending up at different landfills, water stream drains, and channels (Yousuf and Reza, 2011).

5. Environmental and health impact of e-waste

Inappropriate disposal or recycling of e-waste severely affects the environment (air, soil and water), aquatic creatures and human health (Dharini et al., 2017; Huang et al., 2014; Gangwar et al., 2019). If e-waste is stored without using a container, dumped or disposed of or recycled without proper regulation, then there is a huge possibility of mixing the hazardous chemicals of e-waste with soil (Needhidasan et al., 2014), which may leach (e.g., cyanide or mercury-gold amalgam) or washed out from heavy rain to drinking water sources such as river, ponds and underground water.

Figure 5 shows all possible routes of e-waste and the environmental consequences of disposing and recycling e-waste. E-waste producers and receivers follow different routes based upon the treatment facilities, e-waste conditions, and convenient transportation (Perkins et al., 2014). Improper recycling of e-waste has high health and safety risk to associated people such as e-waste collectors and handlers as well as the surrounding community of e-waste recycling facility.

The toxic components in e-waste such as metals (e.g., As, Pb, Hg, Ni, etc.) and organics (e.g., polybrominated diphenyl ethers, poly chlorinated biphenyl, etc.) are the primary toxic substances, which has several health impacts. A summary of hazardous substances, their sources, and associated hazards which are already revealed in different studies are presented in Supplementary Table S1 (Vats and Singh, 2014; Sepúlveda et al., 2010; Leung et al., 2006).

The e-waste associated problems are more severe in developing countries like Bangladesh' since most of the e-waste is not recycled and dumped with municipal solid/liquid wastes without any treatment (Yousuf and Reza, 2011), which results in an increased impact on the employees' health who are involved with the specific operations of e-waste. In Bangladesh, there is a high risk of handling e-waste in the working atmosphere since staff in the e-waste disposal area are unaware of the hazards of handling e-waste and have no personal protective equipment (PPE) to shield themselves (Esdo, 2012). In these workplaces, Chemical Risk Analysis (CRA), Task Risk Analysis (TRA), or Health Risk Analysis (HRA) are not performed properly. The bulk of the staff is
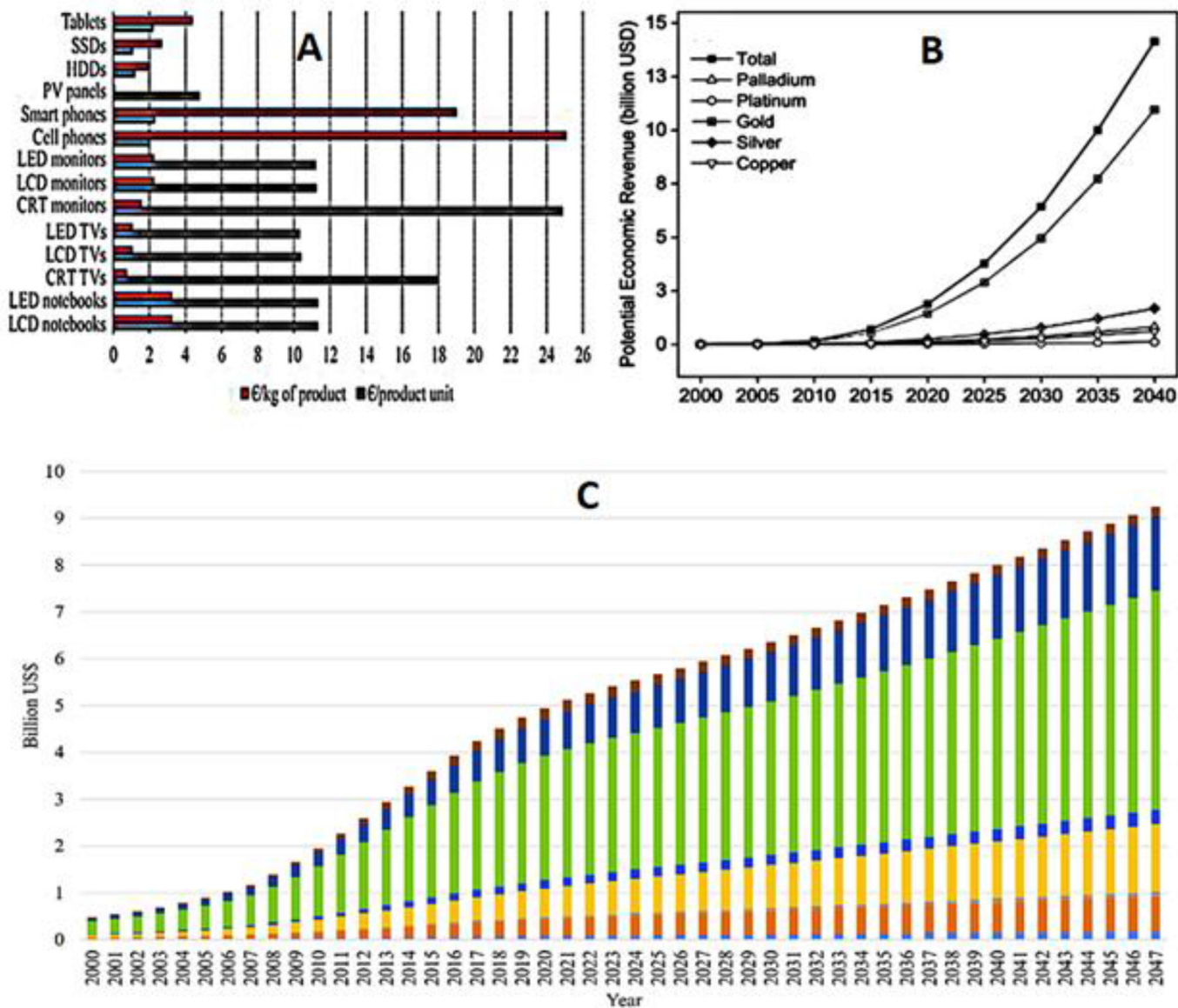
Figure 6. (A) Potential revenue from different e-waste streams (Kumar et al., 2017); (B) Potential economic revenue in USS billion (2000–2040) (Mairizal et al., 2021); (C) Estimated potential revenue of the secondary e-waste materials (Islam and Huda, 2019).

women and children who are completely unaware of their surroundings. As a result, the primary victims of e-waste exposure are staff, children, and women (especially pregnant women). E-waste significantly impacts children workers' health (Karri et al., 2016). According to an ESDO study, more than 83% of child workers involve in e-waste management in Bangladesh are exposed to hazardous and toxic substances present in e-waste. The child workers become sick and survive long-term illnesses. Among them, over 15% die each year (Esdo, 2012). Based on the ESDO report, about 50,000 children are engaged in the unauthorized e-waste collection and recycling process in Bangladesh. Among these children, about 40% are involved in shipbreaking yards. Besides, children may expose to e-waste-derived chemicals and waste of landfill sites in their everyday lives because of unhealthy recycling practices of Bangladesh (Esdo, 2012).

6. The economic aspects of e-waste

E-waste management is an absolute need if we are to keep our environment green and sustainable. The economics of e-waste management play an essential part in the planning phase of the project (Kumar et al.,

2017). In addition, the recovery of economic potential is considered the most promising technique which can be stated as the multiplying of approximately market prices (US$/kg) and the composition of e-waste (g/unit) (Cucchiella et al., 2015). Therefore, an e-waste recycling plant that indicates its return on investment must be situated in proximity to the rail and roadsides to reduce construction and transportation costs (Kumar et al., 2017). Several reports have been investigated regarding the generation of e-waste based on various economic assessments (Ismail and Hanafiah, 2020). Recently, the global demands of precious metals Pt, Au, Ag, Pd, based metals Zn, Pb, Cu, Ni, and rare earth minerals Yt, La, Ce, Nb has been increased significantly in electronic applications such as printed circuit boards (PCBs), computers, smartphones, television, printers, refrigerators, telecommunication servers, washing machines, photocopiers and coffee machines (Rene et al., 2021). Most of the e-waste contains more than 60 different metals (valuable, precious, base, and rare earth metals) and is considered due to their total value share in the e-waste (Bakhiyi et al., 2018). It was reported in London that the total value share was ranging from 85% (PCBs) to 93% (mobile phones) using precious metals (Pt, Pd, Au, Ag), while contributing less than 10% of Fe, Al, Cu, and other base metals (Mairizal et al., 2021). However, the
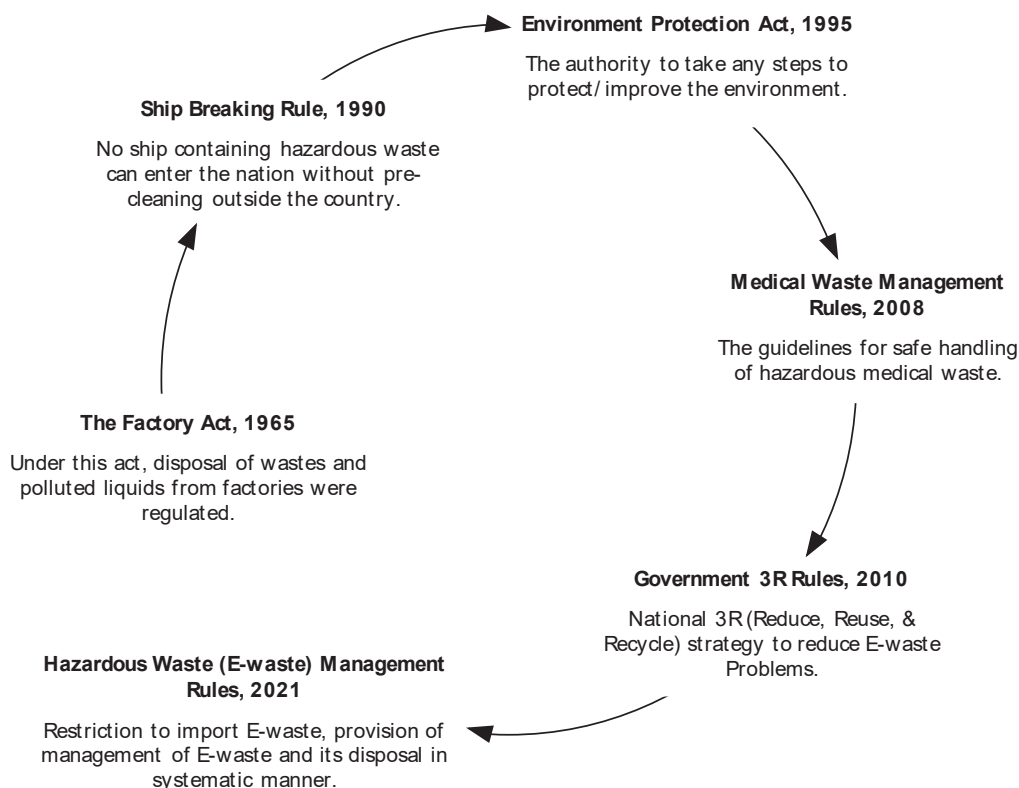
Figure 7. Development of e-waste rules and regulations by the Bangladesh government (Masud et al., 2019).

recovery of precious metals is the major concern towards sustainability. In 2020, the estimated amount of Cu (12.5 MT), Ag (119 MT), Au (21 MT), Pd (54 MT), and Pt (10 MT) can potentially be recovered which market values were US$ 6.45, 2020, 66500, 2184, 97400 per kg of Cu, Ag, Au, Pd, and Pt, respectively (Mairizal et al., 2021). Though the e-waste generation will be increased approximately 60% per capita from 2021 to 2040 that reveals the total economic values of Au, Ag, Cu, Pd, and Pt respectively in the e-waste streams from US$ 2.2 billion to US$ 14 billion. The total expected e-waste materials that contain approximately Cu (95 kt), Au (165 MT), Ag (826 MT), Pd (368 MT), and Pt (109 MT), respectively (Mairizal et al., 2021).

It was investigated that more than 80% of Ag, Au, and PGMs are fixed in screens, monitors, and small IT types of equipment. Among different electronics equipment, PCBs contain over 40% of the total e-waste precious metal value like Ag, Au, and Pd (Kumar et al., 2017). It can be seen that around 1.2 kg of Au, 6.2 kg of Ag, and 0.3 kg of Pd can be recovered from all types of household appliances every year in Chandigarh in India (Ravindra and Mor, 2019). The majority (96%) of precious metal generation can be contributed to ICT-based electronics. Besides annual monetary losses were estimated for those precious metals and found approximately Rs. 3.5 M for Au, Rs. 0.2 M for Ag, and Rs. 0.37 M for Pd, respectively, making a total of Rs. 4.09 M (Ravindra and Mor, 2019). The potential revenue per kg/unit of some e-waste generation is presented in Figure 6A. Based on Figure 6A, the potential revenue of PCBs was $21,200/ton with significant metal concentrations (Borthakur and Govind, 2017). Cucchiella et al. investigated those smartphones, tablets, and notebook are the most important constituent of e-waste due to the presence of a higher volume of precious and critical metals (Cucchiella et al., 2015). Figure 6B reveals the potential of economic revenue from precious metals (Ismail and Hanafiah, 2020). It can be seen that the most precious and other recoverable metals are present in these resources. According to the literature, the total worth of metal and plastic will be recovered and reaches up to US$8 billion by 2040 in Australia.

Thus, the economic national revenue was strengthened by recovering the metal from e-waste in Indonesia (Mairizal et al., 2021). Similarly, Figure 6C represents the potential revenue from the recoverable materials (Forti et al., 2020). The total revenue was increased from US$ 0.48 billion (2000) to US$ 3.59 billion (2015) (Islam and Huda, 2019). The recovery and potential revenue depend on various techniques used for specific types of materials and their waste management system (Islam and Huda, 2019). Meng et al. investigated a promising technology (super-gravity separation) that employed an opportunity to extract Zn, Cu, Pb, and Sn were 80.86%, 93.23%, 94.54%, and 97.67% respectively, from PCBs (Meng et al., 2018).

During e-waste recycling, every item with monetary worth seemed to be gathered and sold to those who could add value to or find purchasers for it. The monetary worth of e-waste varies depending on the composition of e-waste, the country or location where it is processed, and other factors. Therefore, in order to quantify e-waste's economic value, collecting, sorting, and processing materials at various stages of the recycling chain must be considered. Economical values of e-waste can be calculated based on taking average profit in each stage of the recycling chain (Eq. (1)). There are five contributors to the recycling chain: household consumer, scavenger, aggregator, classifiers and processors. Each contributor will earn a profit. As an example, a scavenger paid a consumer $5 for a damaged piece of electrical equipment. The scavenger on the other hand sold it to an aggregator for $7 (profit of $2). Compared to the scavenger, the consumer made a greater profit at this moment. The revenue of aggregators and classifiers is projected to be 5–10 times more than that of scavengers since they collect materials from at least 10 scavengers, households, or home industries. It is difficult to evaluate processors and recyclers since they are located outside the city, have a variety of industries, and do not provide sales records. According to an extensive field survey (Rochman et al., 2017) calculated the average reusable electronic items/parts economical value to be $2.14/kg based on Eq. (1).
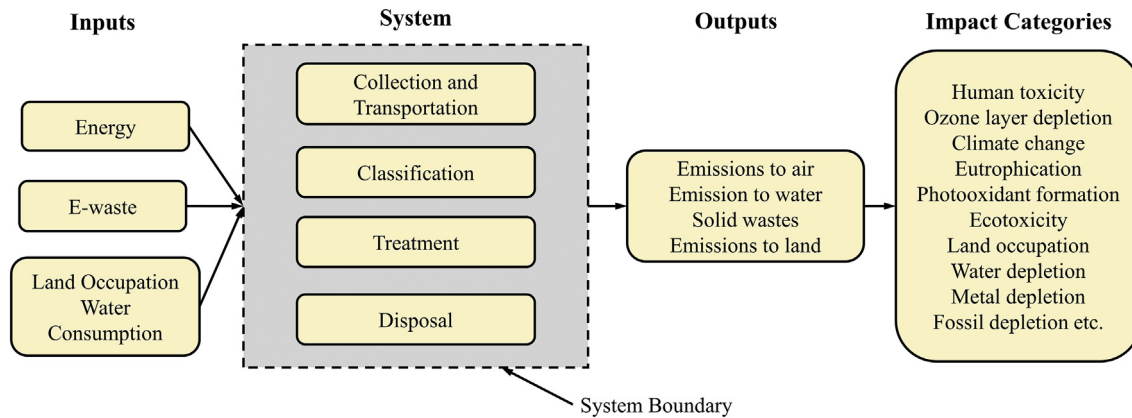
Figure 8. Typical life cycle assessment model for e-waste management (Hong et al., 2015).

Profit calculation = Σ Average selling price - Average buying price   (1)

Based on the above method, Bangladesh could save more than half to one billion dollars within the last five years from 2016 to 2020 if they adopted the idea of complete recycling of e-waste. The economic value of e-waste generated and projected in Bangladesh from 2011 to 2030 is provided in Supplementary Table S2. Bangladesh can earn a revenue of more than 5 billion dollars by 2030. Therefore, economic revenue from e-waste recycling will be a potentially profitable business. More awareness and a proper management system to enhance the recycling process are required. Thus, the authority should take appropriate initiatives to enrich the sustainable recycling of e-waste and provide state-of-the-art training facilities.

7. E-waste management policies and strategies

In Bangladesh, e-waste was first identified as a potential source of harmful chemicals which was incorporated into the medical waste (MW) management guidelines (Yousuf and Reza, 2011). The first draft was done in 2011 by the government of Bangladesh (Alam and Bahauddin, 2015). This draft incorporated some e-waste related legislations, e.g., Ship Breaking Rule'90, Environment Protection Act' 95, Medical Waste Management Rules'08, and Government 3R Rules (Masud et al., 2019). The Bangladesh Environmental Protection Act '95 was updated on June 10, 2021, with the announcement of the Hazardous Waste (e-waste) Management Rules, 2021 (Kengo, 2021). The chronological evolution of the policies has been presented in Figure 7.

The key aspects of this rule are the prohibition on importing e-waste, special concern for fluorescent lamps and mercury incandescent bulbs, and the provision for the management and disposal of e-waste in a methodical manner. This rule has introduced a new dimension to the processing, management, fabrication, and collection of e-waste. It has opened a modified version of the prohibition on the import of any electric and electronic equipment. Despite having different modules, it contains some loopholes that can be comprehended from a deeper level. The Bangladesh Atomic Energy Regulatory Act, 2012 restricts the implementation of the E-waste Management Rules, 2021 to radioactive wastes. There is a prospect of restraining e-waste imports rather than exports. As a result, there is a possibility of a violation through one process. There is no indication of a seminar, meeting, workshop, or public gathering where e-waste issues can be effectively addressed. The E-waste Management Rule contains certain conflicting concerns that must be addressed and resolved through collaboration with the Department of Environment and other authorities in order for it to be properly enforced.

In the past decade, several studies have been conducted on the establishment of a proper e-waste management model (Masud et al., 2019). Therefore, the tools for the management of e-waste are identified to design e-waste collection, recycling and disposal processes. Life cycle assessment (LCA) and Material Flow Analysis (MFA) are developed models considered to be very effective for e-waste management (De Meester et al., 2019).

7.1. Life cycle assessment

Life cycle assessment (LCA) has been established as the process of identifying the environmental impacts associated with all stages of the life of a commercial product, process, or service (Ibáñez-Forés et al., 2021; Xue and Xu, 2017). LCA is a significant tool for managing e-waste and limiting its environmental impact by comparing the environmental implications of various waste management processes (Guinée et al., 2011). Waste management includes handling, treatment, recycling, and disposal (Finnveden et al., 2007; Nakem et al., 2016). LCA can analyze and identify the environmental impact, crucial factors, decisions, and improvement possibilities linked with all the stages of waste management within the system boundary methodically and effectively (Figure 8) (Hong et al., 2015). For LCA, it is necessary to define the system boundary. In most cases, the boundary for studies of LCA for e-waste management does not include the manufacture and use of electronic equipment. Rather, much emphasis was given to the treatment and recycling steps in the studies of LCA (Laurent et al., 2014). The entire LCA process is divided into four steps, which include the definition of the purpose and scope of the process, the analysis of the inventory, environmental and health impact assessment, and interpretation (Liu et al., 2011). In recent years, LCA has been extensively used in research on e-waste management (Ismail and Hanafiah, 2019). It is more extensively utilized in developed countries in Europe for e-waste management research than in developing countries apart from China. Due to the large volume of e-waste generated in China, research into e-waste management is expanding (Song et al., 2013b).

The starting point for LCA in an e-waste management system can be divided into three categories. The first one is the investigation of the environmental impact of one specific electronic product and finding the areas with harmful environmental impact within the treatment process or comparing it to other treatment processes (He et al., 2022). The studies include not only the life cycle assessment of electronic items such as monitors (Bhakar et al., 2015; Rocchetti and Beolchini, 2014), personal computers (Lu et al., 2006), PCBs (Soo and Doolan, 2014; Xue et al., 2015), electronics toys (Muñoz et al., 2009), and other trash but also the metal recovery and recycling during the treatment processes. The second one is the optimization of environmental impact for the electronic waste treatment process taking electronic waste as a whole without specifying a particular product (Song et al., 2013a). The third one is the assessment of the environmental impact, with a particular emphasis on the e-waste collecting system (Xue and Xu, 2017).
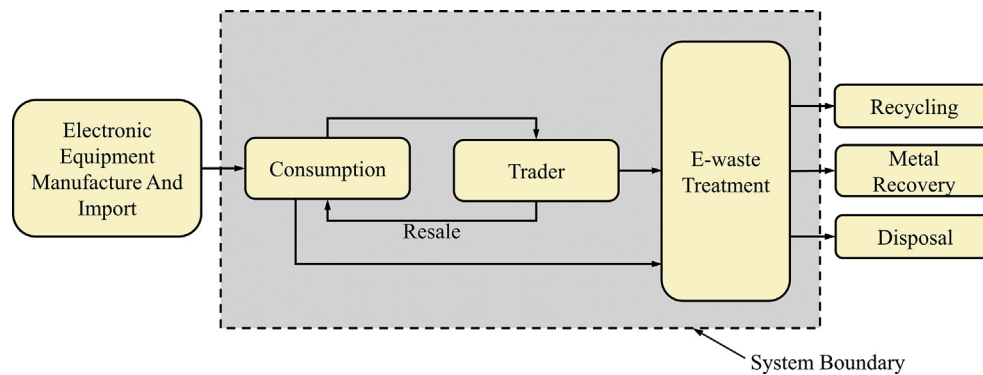
Figure 9. An illustration of a basic material flow analysis model for managing e-waste (Streicher-Porte et al., 2007).

After defining the scope and purpose of the LCA study, it is required to do an inventory analysis. Life cycle inventory (LCI) deals with the input and output of material and energy within the system boundary (Rebitzer et al., 2004). Waste, energy, water, and pollutant emissions to the environment are all part of the input-output balance. To study the inputs and outputs, as well as the processes inside the system boundaries, a flow diagram of the process is necessary (Visentin et al., 2019). Other LCI phases include developing a data collection approach, verifying the data, and evaluating and reporting the results. The life cycle inventory analysis for e-waste management includes the inflow and outflow of material and energy in the e-waste collection, treatment, disposal, and transportation steps (Andeobu et al., 2021).

After LCI, the next step is life cycle impact assessment (LCIA). LCIA is the qualitative and quantitative assessment of the environmental impact of the data obtained from the inventory analysis (Ismail and Hanafiah, 2021). It allows for a better understanding of the harm caused by the usage of resources and emissions. LCIA mainly includes the selection of different environmental impacts e.g., human toxicity, climate change, terrestrial acidification, etc., and then classifying the impact categories based on the LCI results. Additionally, it quantifies the potential impact for different impact categories based on emissions and resource usage and normalizes the impact outcomes in accordance with a reference for comparison of the impact factors (Muthu, 2014). There are several methods for LCIA for quantifying the impacts associated with the system. These include CML 2001, EDIP 2003, EPS 2000, EPD 2007, Eco-indicator'99, TRACI, Impact 2002, ReCiPe, USEtox, etc (Muthu, 2014). Among them, CML is the most widely used in the literature for LCIA of e-waste. Different methodologies use a variety of frameworks and impact categories for analyzing inventory data for impact assessment (Laurent et al., 2014; Xue and Xu, 2017). The methods mainly use a mid-point or problem-oriented approach and an endpoint or danger-oriented approach for LCIA.

The last phase is interpreting the results to ascertain the critical issue, assessing the sensitivity and consistency of the findings, and establishing conclusions and suggestions.

7.2. Material flow analysis (MFA)

Material flow analysis (MFA) is a significant tool in industrial ecology and e-waste management. It is being widely used for the investigation of e-waste management and recycling issues (Figure 9) (Streicher-Porte et al., 2007). MFA has been used to describe materials, products, and substance flows in a territory as well as to analyze the regional and national economies (Graedel and Lifset, 2016; Moriguchi and Hashimoto, 2016). It contains the complete description of each stream within the system. The streams can be physical or monetary. It quantifies all the streams in the system and presents them in both graphical and numerical format. It also includes the analysis of the validity of the results (Graedel, 2019). This methodology is mainly used in the case of complex waste streams including e-waste (Islam and Huda, 2019; Kiddee et al., 2013). MFA for e-waste maps and quantifies the flow of electronic waste in terms of its usage, emission to the environment, and effectiveness of recycling (Graedel, 2019).

The methodology of MFA starts with defining the problem and then the selection of system boundary, substances, and processes are done. After that, the mass and concentration of the flows are determined and balanced. Then the results are presented for visualization and interpretation. These steps are not followed in a sequential manner. Rather, the steps are optimized iteratively. The selections and processes are altered in such a way to meet the objective of the analysis (Brunner and Rechberger, 2016). A typical approach for visualizing MFA results is the Sankey diagram where the quantity of flow is represented by the line width. It is frequently referred to as the "visual language of industrial ecology" (Schmidt, 2008). It is also required to evaluate the uncertainty of the MFA results. The approach to characterize uncertainty in the MFA outcomes was established by (Meylan et al., 2017). Also, the uncertainty in particular flow by varying the color in the Sankey diagram was shown by (Lupton and Allwood, 2018).

The scope of analysis is dependent on the system boundary. The study of MFA has been done at national, regional, or elemental levels. The study of MFA can also be classified as static and dynamic (Withanage and Habib, 2021). The static model analyzes the material and product flow for a constant lifespan of the product for a single year. On the other hand, the dynamic model analyzes the material and product flow for products with a changeable lifetime of more than one year. The dynamic model is used to anticipate the future material flow (Brunner and Rechberger, 2016; Park et al., 2011).

Among the MFA studies for e-waste management, the majority of assessments were made at the national level, accounting for 66% of all assessments. Then it is followed by the regional level, the product level, and the element level assessments (Ismail and Hanafiah, 2019). The products that were considered for MFA studies included personal computers (Yoshida et al., 2009), TV (Singh et al., 2019), mobile phones (Sugiyama et al., 2016), refrigerators (Li et al., 2019), home appliances including washing machine, vacuum cleaner, microwave oven (Lase et al., 2021; Murakami et al., 2006), etc. MFA studies are increasingly focusing on items that include expensive metals like gold, palladium, and silver, such as mobile phones, computers, and laptops (Islam and Huda, 2019; Withanage and Habib, 2021). Most of the national level MFA studies were done in developed countries with a few studies done in developing countries such as India, China, Vietnam, Brazil, Indonesia, etc. There has been a large number of MFA studies in China due to the increasing volume of e-waste generation (Islam and Huda, 2019).

In South Asia, there has been some study of MFA in India (Streicher-Porte et al., 2007).developed a dynamic MFA model for gold and copper flows for recycling personal computers in India is illustrated in Figure 9. The study also included the informal recycling sector and an economic assessment of the material flows. The study of MFA is required

in developing countries for policy-making based on the assessment of MFA results. The current e-waste management system can be modified based on the findings from the MFA model. When it comes to government policy, MFA findings are useful but not imperative. In Japan, 3Rs (reduce, recycle, reuse) policies are designed based on the study of MFA (Takiguchi and Takemoto, 2008). The G8 nations also adopted these 3Rs policies under the 3Rs initiative (Moriguchi and Hashimoto, 2016).

7.3. LCA and MFA approaches in Bangladesh

In Bangladesh, there has been no study on LCA for e-waste management to date. The main reason behind this is the lack of data regarding e-waste and the absence of formalized sector for e-waste management. Not only in Bangladesh, but it is also the case in most developing nations. As a result, there is a large scope for research in this sector. This is required as the environmental impacts are specific to a particular region. This will not only help in improving the e-waste management sector but also in policymaking. The LCA model can be implemented in Bangladesh as it has been applied to different developing countries such as Malaysia (Ismail and Hanafiah, 2019), China (Ismail and Hanafiah, 2019), Pakistan (Shaikh et al., 2020) in spite of lack of reliable data. The impact of a lack of reliable data can be mitigated by making assumptions. The assumptions made for the LCI are such as the environmental impact for the stages before the e-waste collection can be neglected. For the recycling systems, the transfer coefficients and the replacement ratio of the recycled product should be appropriately selected from relevant literature and other sources (Thushari et al., 2020). The assumption must be taken based on site-specific conditions. For establishing the LCA model using various commercial LCA software, the characterization parameters are taken based on Europe or USA. So, the uncertainty derived from the assumptions should be acknowledged while interpreting the results. Other than that, the formalization of informal e-waste treatment and recycling facilities can be a solution for obtaining reliable data. Also, further studies are required to develop region-specific characterization factors for the assessment of environmental impact (Xue and Xu, 2017). The LCA model for current e-waste recycling and treatment facilities in Bangladesh can be developed by using the e-waste data collected from similar studies as it was shown by (Ismail and Hanafiah, 2021). It was recommended for establishing a data inventory for the e-waste management processes. For the LCA model in Bangladesh, the system boundary for the study could be limited to the e-waste recycling zones in Dhaka and Chittagong. The study could be limited to a specific electronic product. After the selection of the system boundary, the data can be collected from the source through surveying and questionnaire. Then using the data obtained, the life cycle impact of the waste management system could be assessed using the different life cycle impact assessment methods. The results must be interpreted keeping in mind the uncertainty derived from the data and characterization factors used. Developing an LCA model from the perspective of Bangladesh can serve as a basis for further study and open the door for a sustainable e-waste management system.

Like LCA, there has been no study on MFA for the management of e-waste in Bangladesh. So, there is a large scope for research in this sector. The lack of data regarding electronic waste is the main obstacle for MFA study in developing countries like Bangladesh. The presence of informal recycling of e-waste and unregulated transboundary movement of e-waste makes it difficult to obtain reliable data. In Bangladesh, the MFA model can be implemented by accounting for the informal e-waste management sectors. The MFA model can be used to assess the role of secondhand electronic equipment traders and other personnel involved in e-waste recycling and management system. Also, the illegal transboundary movement and export of e-waste from developed countries can be quantified using the MFA model. For the implementation of the MFA model, the main obstacle is the lack of availability of reliable data. For the collection of data, a field survey is required. The local NGOs and other
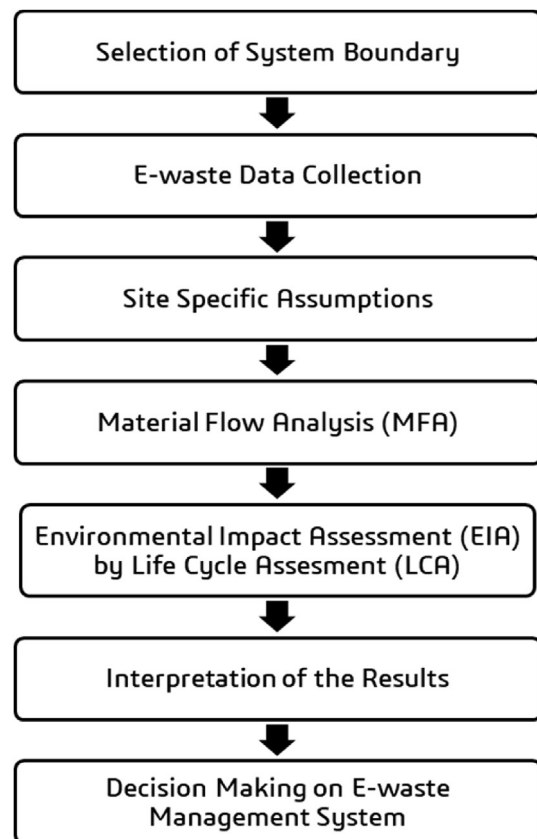

Figure 10. A flowchart for the implementation of integrated MFA and LCA model in Bangladesh.

organizations can also take part and cooperate in these field studies. At the present condition, the study area could be limited to Dhaka or Chittagong considering e-waste from specific electronic products due to the uncertainty of data. There have been several MFA studies in developing countries such as India (Streicher-Porte et al., 2007), China (Liu et al., 2006), Nigeria (Osibanjo and Nnorom, 2008), Vietnam (Tran et al., 2018), etc. In developing countries, MFA studies produce more effective results compared to LCA being a data-sensitive method. But MFA does not evaluate the environmental impacts of e-waste (Kiddee et al., 2013). (Jain and Sareen, 2006) attempted to establish the methodology to quantify e-waste using material flow analysis in India by testing the method in Delhi. In Bangladesh, a similar type of study can be done to quantify e-waste and establish an e-waste trade value chain. Also, the economic aspects of the e-waste management system can be assessed from the results of the MFA model. The study of MFA in Bangladesh will produce information about the flow of e-waste and its trades. The results of the study will be useful for the government for regulating and formalizing the unorganized e-waste management sector.

In the context of Bangladesh, the combined MFA and LCA can also be used for decision-making for different e-waste management alternatives. The flowchart for the implementation of the integrated MFA and LCA approach in Bangladesh is illustrated in Figure 10. In this approach, the outputs, inputs, and connections between the processes involved in recycling and treatment are evaluated by MFA. MFA takes part in evaluating the flows of waste including recycled products and wastes for disposal and treatment (Thushari et al., 2020; Xue and Xu, 2017). The data obtained by MFA is used to evaluate the environmental impacts using the LCA. This approach for integrated MFA and LCA has been used in many developing countries for e-waste management and decision-making, which can be an efficient tool for e-waste management in Bangladesh.
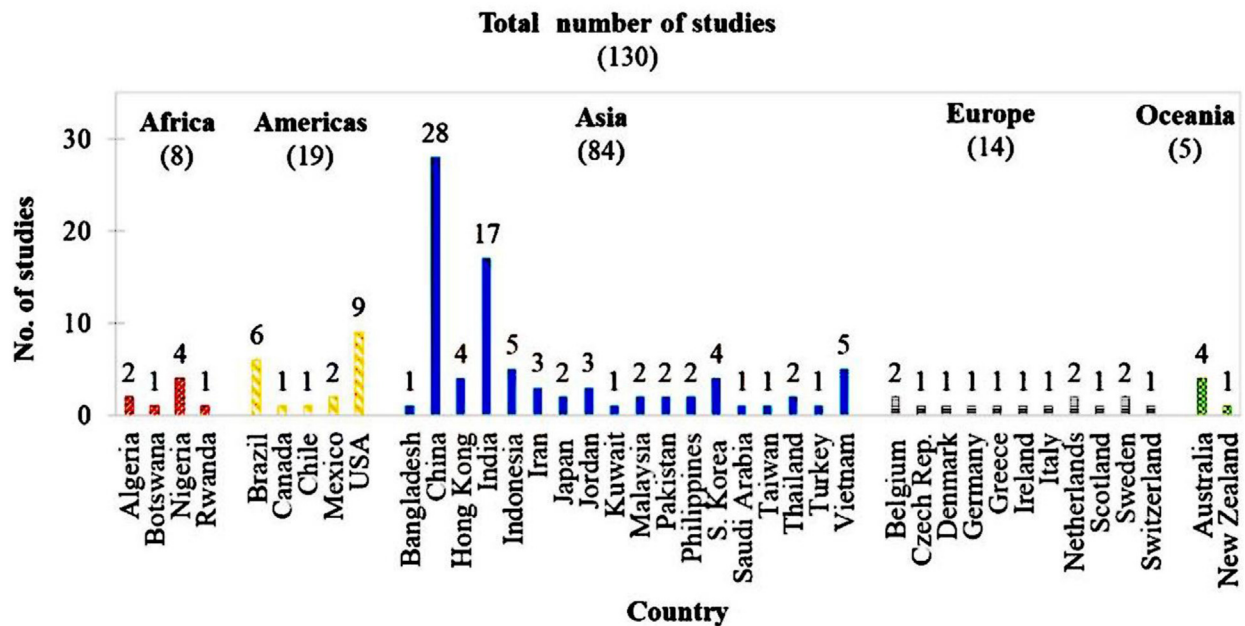
Figure 11. Distribution of publications by geographical area (Ismail and Hanafiah, 2020).

8. Prospects and recommendations for e-waste management

Recently, e-waste management has become a significant challenge concerning developing countries' sustainability. Future studies can focus on developing the e-waste handling process, e.g., collection, disposal and recycling technologies, to obtain a sustainable and greener world (Gollakota et al., 2020). Though the number of research papers based on countries of origin is not enough, the comparison of each country is shown in Figure 7 (Ismail and Hanafiah, 2020). According to Figure 11, only four countries such as China, India from the thirty countries were generated higher e-waste that could be considered a more promising research area. At the same time, more than half of the countries also produced a larger amount of e-waste but were considered less productive due to fewer publications. However, several other publications regarding e-waste generation were excluded. There are several methods for e-waste generation over the years that the researchers should develop and evaluate. This could ensure strong evidence for the researchers so that the methodology can be easily formulated by utilizing different analytical models, techniques, and approaches. It was reported that the evaluation and development of the e-waste stream were at the developing stage and thus received greater interest from researchers in recent years. The main reason in this area was superfluous comprehensive knowledge and art of the state reviews of this research area. This can be solved by using the combination of the newly developed technologies with the existing technologies (Ilyas et al., 2021a). So, systematic research approaches are required in the near future (Rodrigues and Werner, 2019).

Proper documentation is required for the e-waste recycling policy and associated procedure. National television and print media should take a vital role in the proper application of this policy (Nuwematsiko et al., 2021). A formal collection system is a primary objective to reduce the impact of e-waste (Ádám et al., 2021). The integrated e-waste management facilities have to be established based on government policies and legislation. The design should obtain approval from all the relevant governing authorities. The facility has to contain continuous monitoring, control, and data reserving programs to monitor different process variables, compliance with relevant safety protocols, effluents, pollutants, and store incoming and outgoing materials and waste regularly (Ikhlayel, 2018). E-waste should be disposed of after performing all the physical and chemical treatments (Needhidasan et al., 2014). The government

should designate an isolated region for the safe disposal of e-waste. Disposal sites must be advertised after they have been approved, which would create public awareness of the dangerous nature of e-waste. After demonstrating technological expertise and understanding of the dangerous nature of e-waste, the owners and operators of the disposal sites should be approved by the Department of Energy and local governments. The owners and operators should have technological expertise and should understand the consequences of exposure to e-waste (Perkins et al., 2014).

Therefore, various potential factors and strategies should be considered in the future that leads to decreased environmental threats, the probabilities of the risks, and the health hazards associated with the overall e-waste processing. In addition, the following perspectives have been drawn from this study (Arya and Kumar, 2020; Bui et al., 2021; Jadhao et al., 2020; Jaunich et al., 2020; Rene et al., 2021):

  i) Required potential technologies to deal with the dangerous components and to recover valuable metals from e-waste.
 ii) Application of new adsorbents and performing economic analysis for the recovery of valuable materials from e-waste.
iii) Electrochemical-based technology should be applied for the recovery of resources from lamps, small IT types of equipment, cartridges, batteries, hard disks, screens, and temperature-resistant devices from e-waste.
 iv) The optimal supply chain and extended consumer responsibility (ECR) may also be developed and evaluated in the e-waste management rules regulatory.
  v) Based on economic value, suitable recycling systems, and safety awareness should be explored to get the highest profit in an environment-friendly manner.

9. Conclusions

The worldwide e-waste generation is around 57.4 MMT/yr., whereas Bangladesh has crossed the generation of e-waste at around 3.1 MMT/yr. E-waste is detrimental to the environment, and health; however systematic recycling and recovery of metals from e-waste can be a profitable and beneficial business model for Bangladesh. Bangladesh has developed several legislations to control the e-waste stream; however, poor e-waste

handling and inefficiencies of proper training of the localities regarding the severity of e-waste make a complex state for Bangladesh to solve e-waste problems. The annual business potential from e-waste in Bangladesh is approximately equivalent to 221 million USD against 7 billion USD in the world. Economic revenue from e-waste recycling will be a profitable business for Bangladesh. The legislation for e-waste management in Bangladesh; and management strategies e.g., LCA and MFA for efficient waste handling have to be implemented. The combined LCA and MFA approach can be an efficient method for e-waste management in Bangladesh.

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