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Review Article

Revisiting e-waste management: A review of global practices and sustainability

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ABSTRACT

With rapid population growth, as well as, technological advancement, the generation of e-wastes is increasing day by day and has become a fact of emergent concern for scientific and research communities worldwide. Though the most developed territories generate the highest amount of e-wastes, little efforts has been put towards managing them. European countries, including United Kingdom, Germany, and France are managing significant amount of e-wastes responsibly. The informal and unscientific management of e-wastes led to severe health and environmental hazards. The traditional waste management methods, such as, landfilling, and incineration expels significant amount of heavy and toxic chemicals to the environment, leading to severe air, water, and soil pollution. However, proper management strategies for e-wastes not only inhibit the associated harmful effect towards the lives on earth, but also favor circular economy. The sustainability of the strategies for managing e-wastes lie in the responsibility of all stakeholders associated with it. In this review, we have discussed the statistics of global of e-wastes generation and recycling, effect of e-wastes towards lives and the environment, different methodologies of managing e-wastes, and strategies for sustainable e-waste management.

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INTRODUCTION

The rapidly growing population, as well as, modern civilization have revealed a new problem to the environmental and scientific community owing to the disposal of electronic gadgets. A wide range of devices, including consumer electronic e-waste, such as, TV, light, microwave, smart watch, remote control etc. and information communication e-waste, consisting of smartphone, laptop, cellphone, computer etc. can be considered in the category of e-wastes [1, 2]. Problem arises when these electronic wastes are either broken or discarded after use. The rapid industrial and technological advancement in the global scenario have also increased the amount of e-wastes in each year [3]. The inappropriate and unscientific disposal of this waste is not only unprofitable in economic aspect but also detrimental towards lives on earth as it led to several toxic chemicals to the environment [4]. Moreover, with advancements in electronics and modern technologies the lifespan of electronic goods has been decreased substantially. As a result, the electronic wastes increased proportionally with technological modernization. The US Environmental Protection Agency (US EPA) survey suggests an average disposal of 125 million mobile phone each year [5].

Developed, as well as, developing territories like, China, USA, India, Japan etc. generates highest amount of e-wastes in the global scenario [6]. In 2022, the global electronic waste

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generation has reached 57.4 Mt with an average rise of 2 Mt in each year [7]. Out of the total e-wastes collected, only 17.4% are being properly recycled. The e-waste generation is projected to be 74.7 Mt in 2030 [8]. India contributes appreciably good amount of e-wastes in worldwide e-waste generation. The sources of e-wastes constitutes of several types viz., governmental (15%), household (15%), Private (33%) & public (23%). So to manage this high amount of e-wastes policies, principles, complex process should come in operation [9].

E-waste is contains several metals and non-metals as its constituents which make the process of management unique as well as diversified. Typically, the composition of e-waste contains different chemical entities, viz. organic compounds (~30%, e.g., polymers, flame retardant), ceramic materials (~30%, e.g., silica, alumina, mica), and inorganic compounds (~40%, e.g., ferrous and non-ferrous metals). The inorganic part of the waste contain base metals like aluminium, iron, tin, copper etc., noble metals like palladium, silver, gold, etc., heavy toxic metals like, cadmium, nickel, chromium, zinc, mercury, beryllium, lead etc., and rare earth metals like, gallium, tantalum etc. [10]. The existence of toxic hazardous chemicals, such as, mercury, cadmium, lead, chromium (VI), and different brominated flame retardants are responsible in making the management process difficult. In printing circuit boards (PCBs) significant amount of lead is found to be present in addition to copper. These metals are also responsible for environmental and health hazards in the form of liquid crystals in LCDs [11, 12]. The advancement of technologies and advanced features in the smartphones have significantly enhanced the amount of nickel, copper, silver, barium etc. [13]. The improper management of the hazards present in the e-wastes negatively impacts health and environment. In India, the lack of infrastructure and government initiatives for recycling have limited the utilization of e-wastes into useful products and evoked traditional disposal techniques for solid wastes, like, open dumping, land filling, and incineration. These methods are not only economically non-viable but also led to severe air, water and soil pollution [14].

Easy disposal methods, such as, open burning, acid wash, incineration are adopted by countries like India, and China for managing electronic wastes as these methods are easy and economically viable. However, advanced companies like, Noranda, Cimelia, Unicore are following different sophisticated methods, such as, pyro metallurgical, electrochemical, hydrometallurgical technique for recovering non-ferrous metals and utilize them in electronic equipment industry [15, 16]. European territory is doing appreciably good in recycling e-wastes and making useful products and thus saving lives, as well as, environment very effectively. Asian countries are found to be suffered from unmanaged accumulation of e wastes. To reduce waste generation effort should be put in the utilization of different parts of the electronic equipment in some other equipment. This sort of refurbishment will not only help to reduce the cost of the material, but also help to reduce hazards associated with the disposal of the equipment. Small chip level industry could be constructed for refurbishing electronic goods and make them usable [17]. The proper management of e-wastes can only be done by policies from the superior authorities, segregation of the wastes collected and proper research and developments in the field of e-waste management. Not only government initiatives, but also efforts from different non-government organizations, local bodies and most importantly people should come into force to recycle and manage e-wastes and get rid of hazards associated with e-wastes [15].

The prime goal of this review is to investigate the global status of e-waste management and research going worldwide on e-waste management. The evil effects of unscientific disposal of e-wastes on lives on earth and environment have well been explored. In addition, the traditional and systematic procedures of e-waste management can be found in the present review. The utilization of formal and sustainable strategies of e-waste management can led to circular economy. Moreover, several sustainable development goals (SDGs) can be achieved associated with proper scientific disposal of e-waste management.

MATERIALS AND METHODS

This review considers the data published on e-waste management during the span of last twenty years using a distinctive search string in the Web of Science database. The search string in the present investigations was "TS=((((e-waste) OR (electronic waste) AND management))) in the 'Advanced Search' of WoS database for the period 01-01-2004 to 31-12-2023 i.e., last twenty years. This database has proved itself as very much effective in bibliometric analysis as it led to most relevant results. Total 5486 publications were resulted which includes articles, reviews, conference proceedings etc.

Here, the Bibiometrix-Biblioshiny package of R has been employed to quantitatively analyze the bibliometric parameters associated with the e-waste management research [18]. This statistical tool facilitates the growth of the e-waste management research executed by the top five countries. The mostly used keywords, as well as, the sources with average citations per publication (ACPP) have also been studied using this tool.

Global Status of E-Waste Management

Figure 1 depicts different statistical parameters related to e-waste management. As can be observed, the electronic wastes increases in each year and have reached 59.4 Mt. The total electronic waste is projected to be 74.7 Mt in 2030. The continent wise total e-waste generation and per capita waste generation has been depicted in Figure 1b. Although, Asia generated the highest amount of electronic wastes, the per capita electronic waste generation was found to be highest in Oceania. The sources of electronic wastes have been depicted in Figure 1c. As can be seen, small equipment generates highest wastes (32.5%) followed by large equipment (24.4%), temperature exchange equipment (20.1%), screens and monitors (12.5%) and

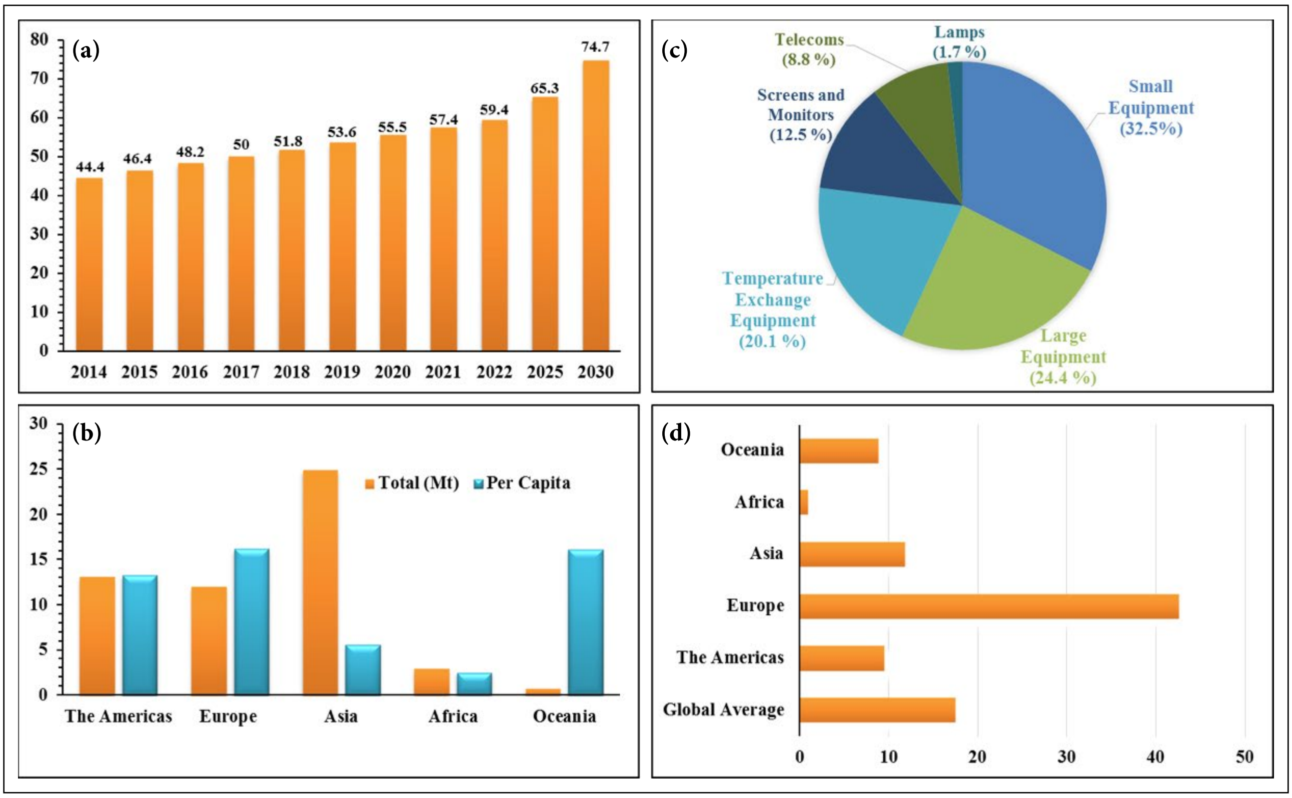

Figure 1. **(a)** Year wise growth in the global electronic waste generation (Mt) with future forecast, **(b)** Total electronic waste generation (Mt) and per capita e-waste generation in different continents of the world, **(c)** Different sources of global electronic waste materials, **(d)** E-waste recycling rate by different continents. Data collected from [19].

Table 1. Country-wise total electronic waste production and rate of recycling [8]

Serial number	Country	E-waste produced (Kt)	Recycling rate
1	China	10129	16%
2	USA	6918	15%
3	India	3230	1%
4	Japan	2569	22%
5	Brazil	2143	0%
6	Russia	1631	6%
7	Indonesia	1618	n/a
8	Germany	1607	52%
9	UK	1598	57%
10	France	1362	56%

telecoms (8.8%). The rate of recycling was found to be highest in Europe (42.5%) as can be observed in Figure 1d.

Table 1 depicts the top 10 countries collecting highest amount of e-wastes and rate of recycling out of the total e-wastes collected. European countries, like, Germany, UK, France were found to possess highest rate of recycling. China produced the highest e-wastes (10129 Kt) with significantly low rate of recycling (16%). India, Brazil, Indonesia was found to recycle at a significantly lower rate (<1%) and found to contribute very poor performance in terms of e-waste management and recycling.

Global Status of E-Waste Management Research

The global status of e-waste management research has been compared in terms of year-wise growth in the number of publications, country-wise production of publications along with year-wise growth, frequency of most used keywords, and journal-wise distribution. The statistical data related to the e-waste management, as revealed from the Bibliometrix-Biblioshiny, has been summarized in Table 2. As evident from the table, the total 5486 documents were published in 1048 sources, which includes journals, conference proceedings, books etc. The annual growth rate is found to be 7.66, suggesting growing interest of research community towards managing e-wastes. The average citation per document (32.21) depicts high acceptability of the documents towards global research communities involving in e-waste management research. The statistical analysis also predicts 7452 keywords in keywords plus and 10957 author's keywords suggesting a wide area covering by e-waste management. On analysing the number of authors, total 13582 authors are found to be authored the documents published on the present topic with the co-authors per document 4.81. It is worthy to mention that the international co-authorship as 29.3%, suggesting appreciably good inter-country collaboration in managing e-wastes. Moreover, the total 5486 documents, published during the twenty years span, includes 4207 articles, 553 review papers. The evaluation of the statistical data on e-waste management suggests the enhanced interest of global community, mention-worthy inter-country collaboration, and versatility of the present topic.

Table 2. Statistical data of the articles published on e-waste management during the last two decades

Description	Results
Main information about data	
Timespan	2004:2024
Sources (journals, books, etc)	1048
Documents	5486
Annual growth rate %	7.66
Document average age	5.89
Average citations per doc	32.21
References	167598
Document contents	
Keywords plus (ID)	7452
Author's keywords (DE)	10957
Authors	
Authors	13582
Authors of single-authored docs	249
Authors collaboration	
Single-authored docs	311
Co-authors per doc	4.81
International co-authorships %	29.3
Document types	
Article	3187
Article; early access	1220
Review	467
Review; early access	286
Others	326

Year-wise Growth in the Number of Publications

Figure 2a depicts the year-wise growth in the number of publications on e-waste management during the span of last 20 years (2004–2023). As can be seen the number of publications were increased with time suggesting enhanced interest of global community towards e-waste management research. If the total twenty years (2003–2022) is divided into four periods of five years, the last period (2018–2022) is found to publish highest number of articles (3077) out of the total (5486) publications. The second last period (2013–2017) followed the last period and 1557 number of articles were published in this period. The year-wise growth in the number of publications suggests an increase in the number of publications on e-waste management in subsequent years. This data suggests the concern of the global community in developing new strategies and processes for managing e-wastes for the sustainability of the environment.

Country-wise Production and Year-wise Growth of Articles

The most productive countries (top ten) in publishing research articles in the field of e-waste management are depicted in the world map in Figure 2b. The data was collected in terms of the designation of the corresponding author. It is mention-worthy that, the highest number of articles (1934) on e-waste management was published from China. This was followed by USA (711) and India (583) publishing appreciably good number of articles in the said field. Other countries with appreciably good number of publications on e-waste management are Australia (287), UK (275), Canada (219), Italy (208), and Germany (188). The distribution of the present research topic among different countries suggests significant research activities around the globe.

Figure 2c depicts the year-wise growth of the e-waste management research executed by the top five countries. It is worthy to mention that the initial five years of research on e-waste management lies in an almost linear zone suggesting very less research focus during 2004–2009. After 2009, the slope of the line readily increases being highest for China. The dominancy in the e-waste management research executed by the authors from China in the entire period considered in this study is well evident from this analysis. This trend was followed by USA and India in the plot representing year-wise growth of number of articles.

Frequency of Mostly Used Keywords

The frequency of keywords (top twenty) used in the present topic is summarized in Figure 3a. As can be seen, 'management' is the most frequently used keywords followed by 'recovery', polybrominated diphenyl ethers', 'electronic waste', 'e-waste' etc. The other keywords with mentionable presence in the articles on e-waste management are 'heavy-metals', 'printed-circuit boards', 'metals', 'brominated flame retardants' etc. The frequency of keywords suggest the association of the present topic with waste management, more specifically solid waste management, environmental and human impact of e-waste and sustainable development of the environment.

Journal-wise Distribution of Articles

The number of articles published in different journals (top ten) on the said topic has been summarized in Figure 3b. It is mention-worthy that, 'Waste management' published highest number of articles (~271) in the field of e-waste management. This was followed by 'Journal of cleaner production' 'Science of the total environment', 'Environmental science and pollution research', 'Resources conservation and recycling', publishing appreciably good number articles in the field of e-waste management. The distribution of journals suggests publication of the e-waste management papers specifically in the field of waste management and environmental science. Moreover, most of the journals publishing articles on e-waste management are of good quality, Q1 journals of international repute.

The average citation per publication (ACPP), an important tool to establish acceptability of the article by the worldwide scientific community has also been depicted in Figure 3b. As can be seen, the ACPP gets maximized for 'Environmental science and technology' suggesting highest citations received by the articles published in the said journal during this time span. This was followed by 'Environmental international', 'Resources conservation and recycling' and 'Waste management'.

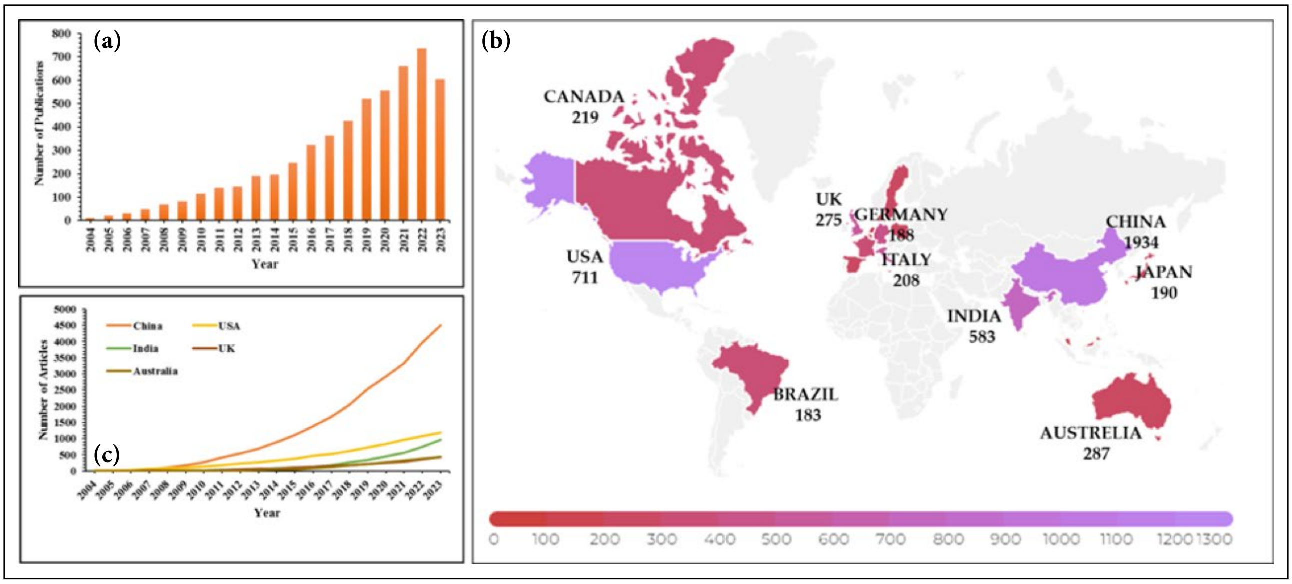

Figure 2. **(a)** Year-wise growth in the global electronic waste management research in the last twenty years (2003–2022), **(b)** Most productive countries doing research in e-waste management, **(c)** Top twenty keywords used in the articles on e-waste management.

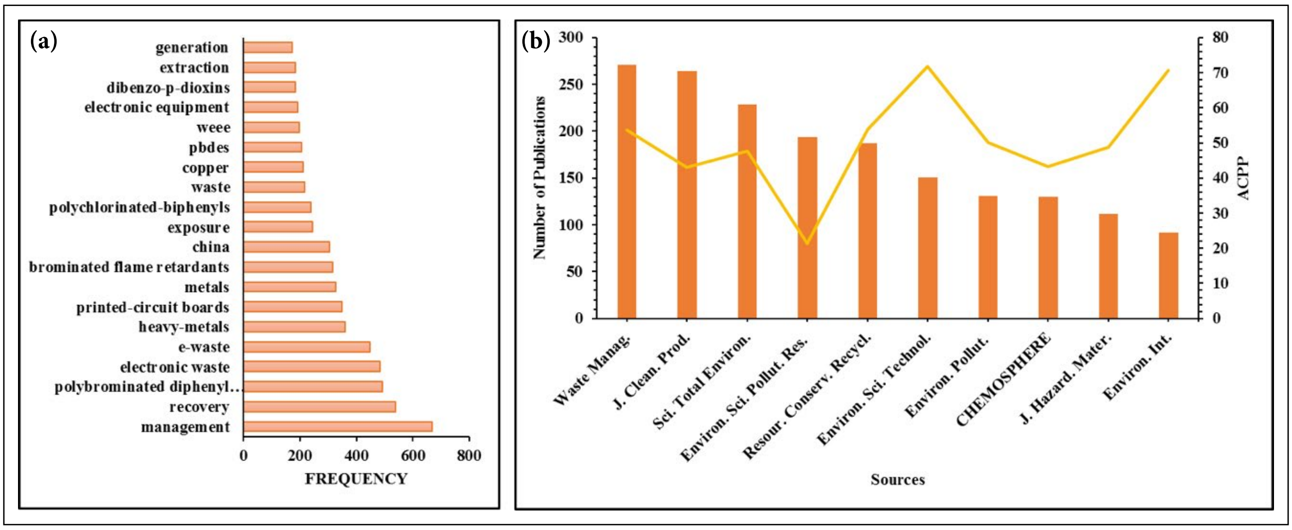

Figure 3. **(a)** Top twenty keywords used in the articles published on e-waste management, **(b)** Top tenjournals publishing articles on e-waste management along with average citations per publication.

The intensive investigation of the research articles published on e-waste management in the last two decades span is the motivation for discussing the environmental and health hazards, conventional processes (such as, landfill disposal, reuse, recycling, metal recovery from waste PCBs), and advanced processes [such as, lifespan extension (LE), life cycle assessment (LCA), materials flow analysis (MFA), multiple criterion analysis (MCA), extended producer responsibility (EPR) and extended consumer responsibility (ECR)] in a single review. Owing to the social responsibility, as well as, environmental benignity, the sustainable e-waste management favoring circular economy has also been highlighted.

PROBLEMS WITH E-WASTE

Electronic wastes contain many toxic chemical entities. The lack of proper disposal and management is threatening for health, as well as, environment. Scientific and research communities around the globe are actively engaged in research devoting in the management of electronic wastes to minimize the hazards associated with these toxic chemicals towards lives and the environment [20, 21]. The conventional practices of waste disposal, like, open dumping, landfill, incineration can causes soil, water, and air pollution [22]. Different electronic parts are associated with different hazardous chemicals and thus require complex procedures to manage these hazards and to get rid of the pollution associated with e-wastes.

Impact on Human

E-waste can affect human health in two different ways-

(1) Food chain issue: e-wastes contaminates food on open dumping through coming into the food chain and become a part of food eco-systems

Table 3. Hazardous chemicals, their sources and their impacts on human health [22–28]

Hazardous chemicals	Sources	Effects
Arsenic (As)	Microchips	Can cause several skin diseases along with lung cancer, liver and kidney diseases. Increases the rate of heart attack and significantly retard birth weight of child with associated neurological disorders.
Lead (Pb)	CRTs, TV, monitors, PCBs	Can severely damage nervous systems in children; Can affect blood circulation, reproductive as well as, nervous systems in adults.
Mercury (Hg)	LCDs, CRTs, PCBs, thermostats, sensors	Can damage brain and central nervous system badly; It can also damage kidney, liver, and immune systems. Inhibit fatal growth.
Cadmium (Cd)	Batteries, PCBs, CRT glass, toners, plastics, and infrared detectors	Highly toxic on human consumption. It can damage severely kidneys, bones and reproductive systems.
Antimony (Sb)	Semiconductors and PCBs	The exposure to antimony can produces skin problems like, redness on the skin, dermatitis etc. It can also cause headache, nausea, vomiting, insomnia, and abdominal pain.
Chromium (Cr-VI)	PCBs and metal housings as corrosion resistant	Highly toxic human carcinogens. It can affect reproductive systems and endocrines in human body.
Beryllium (Be)	Computer parts, electrical boxes, ceramic components	Can severely damage lungs, heart, liver, kidneys and central nervous systems.
Nickel (Ni)	Ni-Cd batteries, CRTs	Accelerates lungs, heart and neurological diseases.
Barium (Ba)	CRTs, fluorescent lamp	Can led to cardiac and respiratory failure, gastrointestinal dysfunction, and even paralysis.
Cobalt (Co)	Rechargeable lithium-ion batteries	Cobalt can yields asthma like allergy, such as, wheezing, cough. It can also led to heart, thyroid and kidney diseases.
Lithium (Li)	Batteries	Exposure to lithium can led to nausea, diarrhoea, dizziness, muscle weakness, and fatigue.
Polyvinyl chloride (PVC)	Wires and cables	Management of PVC through incineration produces chlorinated dioxins and furans which remain in atmosphere for longer period causing respiratory diseases on inhaling.
Zinc (Zn)	CRTs, batteries	Can cause Cu deficiency (anaemia and neurological disorders)
Brominated flame retardants	Boards and casing of electronic components	Can sustain in environment for longer period, neurotoxicity. Long exposure can affect learning and memory functions along with hyper and hypothyroidism.

(2) Direct exposure to worker: The conventional practice of waste management led to toxic chemicals inhaled by the worker during incineration. The direct exposure of these toxic chemicals led to several health damages.

Different hazardous chemicals originated from electronic wastes, their sources and their impact on human health has been summarized in Table 3. As can be seen, different electronic components contain significant amount of hazardous chemicals, which includes both heavy metals, toxic polymers and flame retardants. Heavy metal, such as, Pb and Hg can severely affect the central nervous system of human body. Lead is reported to adversely deteriorate the mental health of kids along with damage in the reproductive and renal systems [29]. Pregnant women are prime sufferers from mercury, affecting fatal growth. Figure 4 represents the health hazards associated with the toxic chemicals liberated from e-wastes on disposal. As has proved itself to be very lethal to mankind, causing lungs, kidney, and liver cancer along-with severe cardiac arrest. The detrimental effect of other elements like Sb, Cd, Cr(VI), Be, Ni, Co, Li etc. is also worthy to mention. Human gets exposed in a variety of pathways to the e-wastes. The informal sectors close to the e-waste disposal, as well as, recycling facility are the main victims for such kind of pollution. According to International Labour Organization, the kids of the family of these workers get contaminated easily with these lethal elements and chemicals, often designated as home exposure [30]. The unscientific disposal of e-wastes in dumping ground led to the contamination of soil from the hazardous metals present in it. The toxic chemicals thus come into the food chain, showing its lethal action to the human on exposure. A study by Tsinghua University, China suggests absorption of majority of toxic chemicals through nutritional path, during disassembling work [31].

Impact on Environment

The unplanned and unscientific disposal of e-wastes is harmful not only towards human being but also towards environment. Conventional practices of waste management, such as, incineration, open dumping, landfill may accelerates severe damage to the environment. Figure 5 depicts the adverse effect of the unscientific e-waste management practices towards the environment. As can be observed, air, water and soil may get polluted associated with the usual procedures of electronic waste management. The disposal of e-wastes through landfilling or open dumping

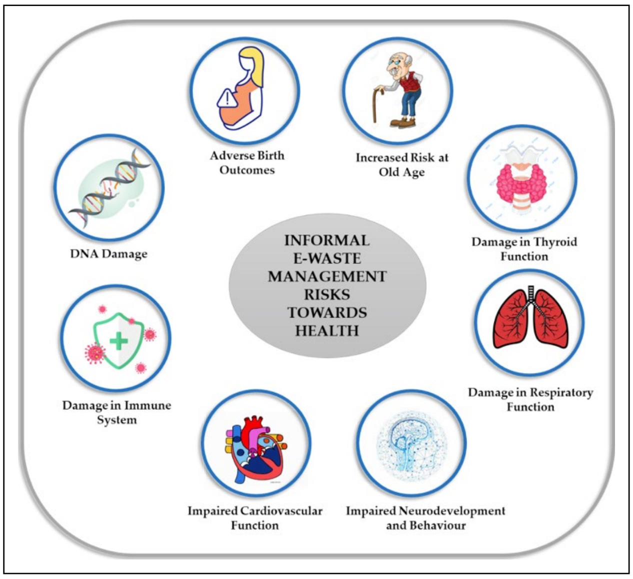

Figure 4. Impact of informal e-waste management towards human [32].

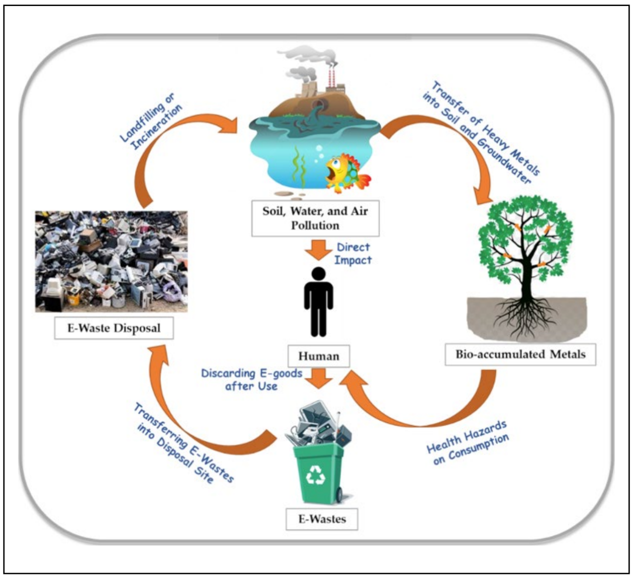

Figure 5. Impact of informal e-waste management towards environment [35].

may contaminate the soil by virtue of the presence of the heavy metals and other organic pollutants in the waste materials. Moreover, the leaching of these hazardous materials may lead to the contamination of ground water resulting water pollution. The presence of heavy metals, and organic matters in soil may affects plants, microorganisms, crops etc. The heavy metals may thus come into the ecosystems and displays its harmful effects towards the lives on earth. Additionally, the existence of the toxic chemicals in the soil changes the pH of the soil, destroys the micronutrients, affecting adversely the growth as well as its productivity. The ground water may become polluted in addition to soil pollution as consequence of open dumping or land filling of the electronic wastes. The water bodies as well as the animal kingdom may get suffered due to the presence of the toxic entities in the ground water. The quality of drinking water may get deteriorated associated with the presence of the heavy metals and other toxic pollutants and thus the existence of biodiversity become questionable [33]. The management of e-wastes in terms of incineration may degrade the quality of air by enhancing the amount of the harmful chemicals in terms of particulate matter in the air. Living beings may get damaged physically associated with the inhalation of the toxic chemicals during respiration.

The electronic waste management thus negatively impact environment and lives in the ecosystems. The human being, including adults, pregnant women, and children suffer badly from the e-waste pollution. Proper precautions need to be undertaken in managing the electronic wastes to maintain the sustainability of the ecosystems [34].

E-WASTE MANAGEMENT PROCESSES

The end usage of electronic wastes necessities the management of these accumulated wastes to minimize its harmful effects towards the environment and the lives on the earth. As the reuse, refurbish, or recycling strategies involve utilization of the e-wastes in other purposes, it is expected to evoke less harm towards the environment and the health. Some important e-waste management strategies has been discussed below.

Landfill Disposal

Landfilling is considered to be most common and easiest way of disposal of any solid wastes. Disposal of electronic wastes through landfilling has proved itself to be the most convenient way of e-waste disposal. The landfilling of e-wastes results in the release of polluting metals and other hazards naturally into the environment for years, leading to the severe damage to the ecosystem. The disposal of batteries through landfilling may led to the leaching of mineral acids and heavy metals, such as, nickel, lead, mercury, cadmium into the soil and also to the groundwater [36, 37]. The presence of these heavy metals into the soil, as well as, in the ground water leads to the contamination of rivers, ponds, and streams. Animals and individuals are found to be suffered from serious health issues associated with the toxicity of the metal ions and other pollutants [38]. Organic materials are also found to display their hazardous activities associated with their degradation into toxic fragments [39].

Thermal Treatment

Electronic wastes can also be disposed of through thermal processes like, incineration and pyrolysis. Incineration involves discarding electronic wastes through burning instead of landfilling them [40]. This process involves the reduction of the volume of the waste materials through burning and the energy recovered from the burning of combatable material can be utilized to carry out other processes. On the other hand, pyrolysis leads to the conversion of the waste materials into fumes, oils, and charcoal. The burning of PVC or plastic boards generates toxic gases consisting of polycyclic aromatics, dioxins, and polychlorinated dibenzofurans. Additionally, several gases of carbon, sulfur, and nitrogen along with the emission of heavy metal oxide occur. In spite of the simple and economically viable process, the thermal processes are generally avoided owing to their significant evil effects towards the environment [41, 42]. In addition, the incineration plants are reported to gather significant amount of cadmium and mercury [43, 44].

Reuse Process

The refurbishment process offers the reuse of the electronic wastes after minor repairing. The repairing of the electronic wastes not only favors its use for the second or third time but also helps to reduce the generation of electronic wastes. However, the process of refurbishment sometimes gets retarded owing to the least interest from the stakeholders.

Recycling Process

Recycling involves physical procedures to make the waste material competent in the same or some different application. The components of the waste materials are recovered by disassembling followed by disintegration. The recycling process has established itself as an efficient method for recovering valuable materials from wastes and utilizes them in some other purposes. As the process involves reutilization of the waste materials in some purposes, it is expected to inhibit pollution associated with the disposal of electronic wastes into the environment along with the restoration of the non-renewable virgin polymer. The recycling process thus found to save significant amount of energy [45]. The key goal of recycling is to minimize the contamination of the environment by the hazardous toxic chemicals from the electronic waste scrap and ensure the recovery of maximum material. For effective recycling, proper strategy needs to be adopted for the electronic waste material under consideration [46].

Recovering Metals from Waste Printed Circuit Boards (PCBs)

Printed circuit boards are inevitable part of any electronic product and thus with technological growth the amount of electronic wastes consisting of PCBs are also found to be increased. PCBs require special attention during management owing to their complex structures along with the presence of different kinds of materials [47]. PCBs are typically consists of three parts, viz., an insulating laminate, metallic conducting path, and different types of electronic components, including integrated circuits, registers, processor, transistors, capacitors etc. The insulating laminate is found to contain glass fiber reinforced plastics and some flame retardants. Several polymers, such as, polypropylene, epoxies, polyethylene and polyesters are generally utilized in the fabrication of PCBs [48]. The PCBs are thus required immense attention during their disposal. The unscientific and informal disposal of PCBs is not only a great threat towards the health and environment but also led to significant economic liability owing to the loss of valuable metals during treatment. Several methods have been developed by scientific communities around the globe to recover the valuable metals present in the PCBs and control the pollution associated with the disposal of these PCBs. The recovery process consists of three steps: pretreatment of the waste, their size reduction, and metallurgical treatment of the crushed wastes. The pretreatment step consists of disintegration of the board along with its compositional analysis [49]. After pretreatment the board is then shredded and screened according to the size [50, 51]. The third step consists of metallurgical techniques for recovering valuable materials as discussed below. Figure 6 summarizes different procedures for recovering valuable metals from waste PCBs.

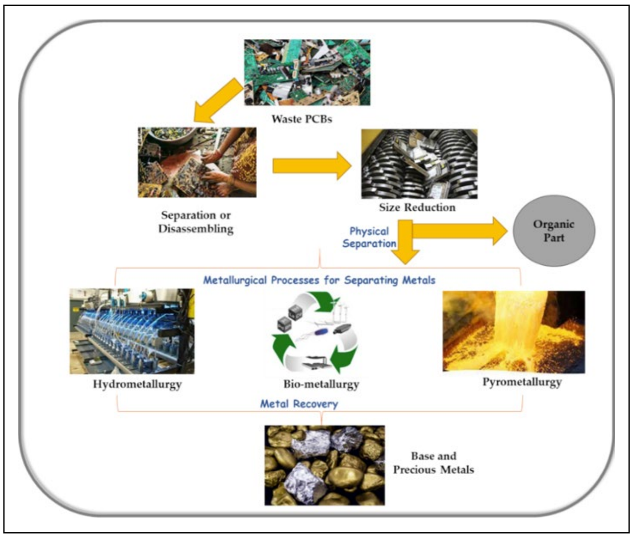

Figure 6. Procedures for metal recovery from waste PBCs [63].

Pyrometallurgical Processes

Pyrometallurgical processes offer several types of thermal treatments, which include smelting, sintering, drossing, and melting at elevated temperature [40]. These processes are used along with the thermo-physical separation of metal phase from the waste PCBs. For efficient and faster separation of metal from PCBs appreciably high amount of energy needs to be provided [52]. During industrial processes, the maximum energy can be utilized by several pre-treatment processes like, physical segregation, dismantling before smelting; a copper alloy consisting of precious metals typically generated [53, 54]. Pyrometallurgy is generally utilized in the separation of a metallic part from the non-metallic slag; the incineration of the organic component occurs. The other metal recovery processes, such as hydrometallurgy, biometallurgy are generally combined with pyrometallurgy to recover individual metals effectively [48].

Hydrometallurgical Process

Hydrometallurgical process is executed for recycling the metallic part present in the printed circuit boards economically. This process involves dissolution of the waste materials into the mixture of strong acids or bases, such as, sulphuric acid, hydrochloric acid, nitric acid, aqua regia, and alkalis [55]. The preferred metal can be extracted from the metal solutions by processes like electrorefining, adsorption, precipitation, solvent extraction and ion-exchange [56]. In developed countries, the recovery of metals from electronic waste materials was initiated in the late 1960s [57]. Precious metals, like silver and gold can be recovered in highly refined form employing this hydrometallurgical procedure [58]. The leaching solutions were found to be altered in different period of time. Cynaide leaching was widely employed for a longer period for extracting silver and gold in the form of dicyanoaurate or dicyanoargentate complexes [59, 60]. However, owing to the toxicity of cyanide, several non-cyanide leaching reagents, such as, thiosulphate, thiourea were proposed as the alternative leaching agents in the later period [61, 62].

Biometallurgical Process

Biometallurgy is actually the combination of two processes, viz., bioleaching and biosorption. Biosorption involves physico-chemical interaction between the microorganisms and the ions present in the solution. The microorganisms may be in the alive or dead condition. Various microorganisms, viz., algae [64–66], bacteria [67, 68], and fungi [69] are efficient in isolating heavy, as well as, precious metals from electronic wastes. Sheel and Pant [70] have recently reported a novel method involving leaching-sorption for recovering gold from e-waste utilizing ammonium thiosulphate and Lactobacillus acidophilus. Biosorption, as compared to the conventional method of metal isolation, provides several advantages, including, low operational charges, handling of less chemical sludge, and its high efficacy towards the process [71, 72]. Mack et al. [72] isolated gold (III) from leached wastes using Desulfovibrio desulfuricans biomass. The success of the bioleaching process is directly related to the efficacy of the microorganisms in the transformation of the solid compounds into soluble form. Several microbiological leaching processes have been executed in the last twenty years to mobilize metals from electronic wastes [73–75]. Acidophilus microorganisms, such as, Acidithiobacillus ferrooxidans, Acidithiobacillus thiooxidans, and Leptospirillum ferrooxidan has been reported as efficient microbe in the bioleaching process. Penicillium and Aspergillus niger are reported as efficient fungi in the isolation of metals from industrial wastes [76]. Another efficient method of bioleaching involves redoxolysis in the presence of acids and complexes [77, 78].

ADVANCED PROCESSES OF E-WASTE MANAGEMENT

The advanced formal processes of e-waste management involves different novel terminologies, such as, lifespan extension (LE), life cycle assessment (LCA), materials flow analysis (MFA), multiple criterion analysis (MCA), extended producer responsibility (EPR) and extended consumer responsibility (ECR). These systematic procedures have been adapted by developed countries to inhibit the pollution associated with e-wastes and uplift the environmental quality. The sustainable e-waste management starts with collection, separation and segregation of the waste materials followed by procedures for recovering precious metals. The parameters related to systematic e-waste management has been discussed below.

Lifespan Extension (LE)

Lifespan extension can be considered as a effective way for reducing e-wastes. Product's lifespan is defined as the period starting from its operational start to its discarding by the end owner [79]. This period consists of any kind of repair, refurbishment, and hibernation, when the product is not in use. As soon as the product is disposed off it comes into the environment as e-wastes and displays its aggravating effects towards the environment. To minimize its impact European Commission encouraged the extension of product's lifespan [80]. Bakker et al. [81] suggested an optimum lifespan of refrigerator 20 years and that of a laptop 7 years. These values are far greater than the average lifespan of 14 years and 4 years for refrigerator and laptop, respectively. Elevli found that the periodic maintainence and upgradation can effectively extend the lifespan of computer [82]. However, the technological advancement have limited the lifespan of e-products, such as, computers, laptops, smartphones, tablets, washing machines etc. The new technologies developed in the era of its operation have directed consumers towards replacing old gadgets by the newer one.

Life Cycle Assessment (LCA)

Significant research effort has been put towards LCA of electronic gadgets in relation to eco-friendly design, and environmental hazards. The environmental, as well as, economic impacts should be taken into consideration towards designing electronic device. LCA, for instance, offers systematic inhibition of environmentally pollution creating parameters, such as, carcinogens, ozone layer, climate change, soil character etc. The geographical distribution of LCA tool in the e-waste management suggests its initiation in Europe, followed by other continents like Asia, North America etc. [83]. It is worthy to mention that, Europe started its attention in the e-waste management two decades back, and thus has become technologically sound with time. Thus, the recycling and reuse of the e-waste materials is well administrated by the laws of European Parliament, restricting emission of hazardous substance into the environment. EU is considered as the pioneer in utilizing LCA tool in managing e-wastes. There has been extensive research conducted on LCA to assess the environmental consequences associated with the end-of-life (EoL) treatment of e-waste. For instance, the tack-back policy of e-wastes in Switzerland and its impact on environment was explored well by Hischier et al. [84] As observed, the take-back policy along with recycling appeared to be superior as compared to that of conventional incineration process owing to the sustainability of the environment and human health. The study by Barba-Gutiérrez et al. [85] revealed recycling of e-waste materials to be the most effective way for treating e-wastes considering the aggravating effect of the respiratory hazards towards the human health.

Material Flow Analysis (MFA)

The export of e-wastes from developed countries to the developing territories like India, China for reusing or recycling purpose were executed before the restrictions associated with the Basel Convention come into the force. The MFA technique is employed for examining the trajectory of materials, specifically e-waste, as it moves towards recycling facilities, disposal sites, and material stocks over a given period. This approach establishes connections between the origins of materials, the pathways they follow, and their ultimate destinations, encompassing both intermediate and final stages. MFA have proved itself to be very efficient tool within the realm of environment and waste management and thus this tool can be utilized in designing proper e-waste management scheme considering its economic, environmental, and social impact [86]. For instance, the flow of e-wastes in Asia was explored well by Shinkuma and Nguyen Thi Minh; the second-hand e-waste materials from Japan were reused in countries like Vietnam, Combodia etc. while the majority of e-wastes were informally recycled by China [87]. Aydin [88] utilized this MFA tool to optimize the capacity of solid waste management in Ankara, Türkiye. Streicher-Porte [89] employed MFA in conjunction with economic value assessment to conduct a comprehensive system analysis of the flow of Au and Cu derived from personal computer recycling in India. Their findings indicated that due to the significant concentrations of Au and Cu present in the recycled materials and the high value associated with these metals, recyclers were able to generate profits.

Multi Criteria Analysis (MCA)

According to Garfi et al. [90] MCA is defined as a strategic tool to resolve the complex issues considering qualitative, as well as, quantitative aspects of a problem. This tool has proved itself to be an efficient tool in the sustainable e-waste management to get rid of the environmental, as well as, health hazards associated with it. For instance, this MCA tool was utilized by Hula et al. [91] to optimize the management of waste coffee maker in terms of environmental sustainability and economic benefits.This modelling approach can also be applied in setting up methodology, as well as, selecting proper location for the establishment of new industries for recycling of e-wastes. For instance, in Spain, the MCA tool was utilized in selecting the best location for establishing e-waste recycling plant [92]. The selection process was based on the quantitative parameters involving warehouse location and economic aspects. The alternative processes of e-waste management were also designed computationally by Rousis et al. [93] Twelve different management strategies were compared and numbered according to their efficacy and suitability. The most effective way is to disassemble the complete e-waste part followed by processing for recycling of the eligible part; the remaining part can be discarded as landfilling. Although MCA is not a widely accepted tool in the e-waste management, it is generally utilized in addition to other tools to fulfil the social responsibility associated with the e-waste hazards [29, 94].

Extended Producer Responsibility (EPR)

The EPR approach is an environmental policy that assigns liability of the manufacturers for reclaiming products once they are no longer in use; it is operated on the basis of the polluter-pays norm [95]. This EPR policy is widely imposed in advanced nations, like European Union, Japan, and some parts of United States and Canada. This policy was initiated in 1991 by the EU and came into regulation in 2004 for taking back the e-wastes for treatment and recycling. The WEEE Directive (Directive 2002/96/EC) of the EU was formulated to establish regulations concerning electronic waste and its management. These regulations were developed with the principles of EPR in mind. The legislation sets forth the responsibility of producers in managing e-waste throughout its lifecycle, ensuring environmentally sound practices for EoL activities such as reuse, recycling, and recovery of electronic waste (EU, 2002). In the late 1990s, Japan introduced an environmental policy that focused on the responsibility of managing electronic waste (e-waste). This policy is regulated through two key laws: the Specified Home Appliances Recycling (SHAR) Law and the Electric Household Appliance Recycling Law. The SHAR Law was promulgated in 1998 and became effective in 2001. These laws establish regulations and guidelines for the recycling and proper disposal of electronic household appliances in Japan [96]. The SHAR law was implemented to facilitate the collection and proper disposal of electronic waste, specifically targeting large household appliances such as television sets, refrigerators, air conditioners, and washing machines. This law ensures that these items are taken back for recycling and appropriate treatment. Additionally, Japan has the Promotion of Effective Utilization of Resources (LPUR) Law, which addresses the management of personal computers and used batteries, aiming to promote their effective utilization and proper disposal to minimize environmental impact [97]. Additionally, this EPR policy also escalated Design for Environment (DfE) during fabrication of new electronic product. The electronic manufacturers have successfully developed printed circuit boards devoid of lead bromine to get rid of the environmental hazards associated with them [14].

Extended Consumer Responsibility (ECR)

The success in effective e-waste management lies in the perception of consumers towards e-wastes in addition to the government and producer based initiatives [98, 99]. ECR in e-waste management refers to the active participation of consumers in the systematic e-waste management and thus escalating recycling, minimizing the environmental and health hazards associated with it [100]. The detrimental effects of e-wastes appear to be very much unrevealed to the consumers [101]. In addition, people sometimes do not agree to consider e-wastes as hazardous, as well as, toxic [102]. This is a very common scenario in both the developing and developed countries. In USA, for instance, the unwilling of consumers restrict-

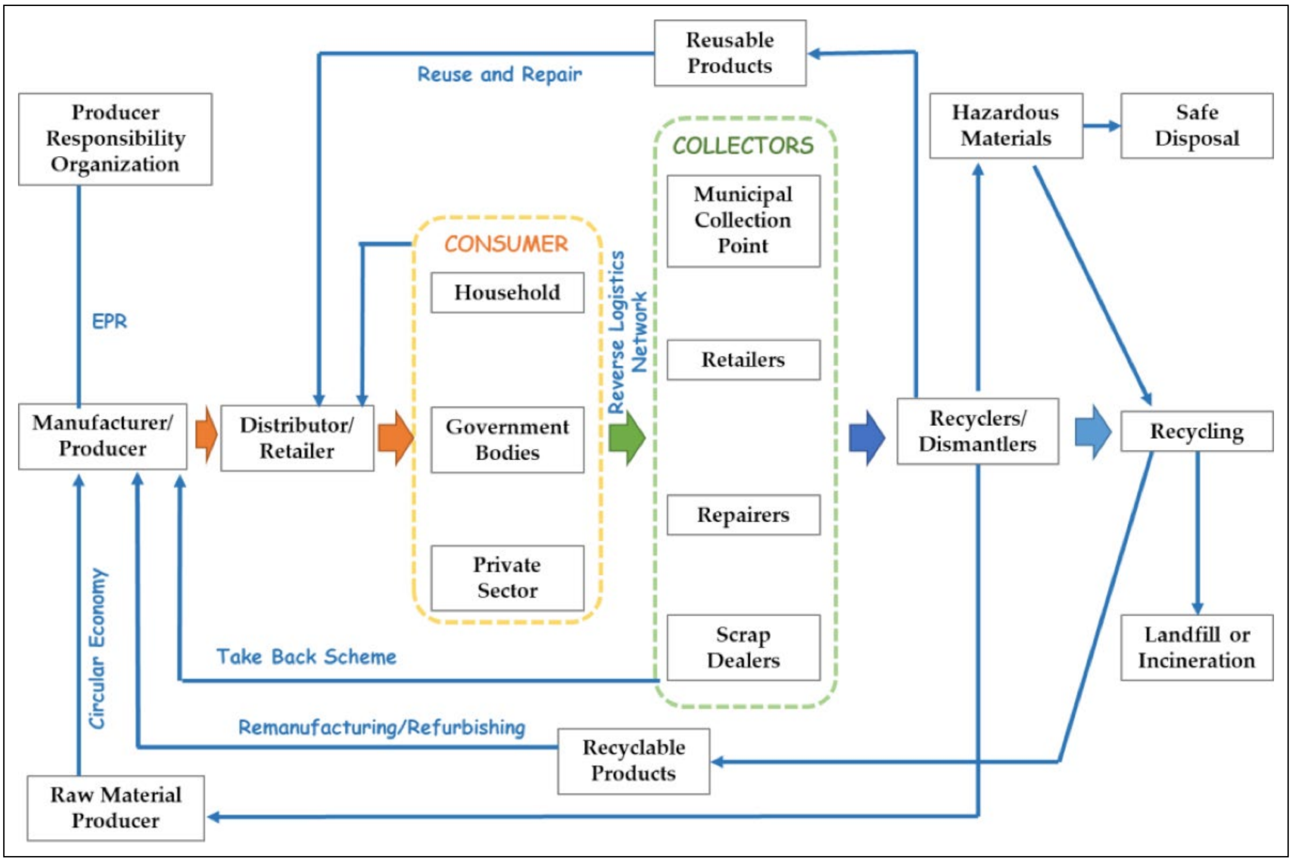

Figure 7. A sustainable approach for e-waste management, adapted from [106, 107].

ed themselves in transferring the e-waste materials to the recycling facilities associated with the lack of consciousness, as well as, inadequate information available with it [103]. Siringo et al. [104] suggested the environmentally sustainable practices in individuals can be achieved through the change in behaviour through motivation. The morality, environmental concern and social responsibility are expected to direct individual to promote sustainable practices like recycling. Governments and non-governmental organizations can play a vital role in educating consumers through awareness campaigns and endorsing legislation that promotes EPR.

Utilization of Each Distinct Tool in the Systematic E-Waste Management

The success in the proper e-waste management lies in eco-friendly design, proper scientific collection of e-wastes, recovering/separating precious/hazardous metals by safe procedures, recycling the eligible part, safe disposal of the remaining part, and raising awareness in the producers and users. Most of the developed countries and also few developing countries are following these strategies for managing their accumulated e-wastes. Some developing countries are still struggling over to establish proper network for e-waste management. Proper training of the users, as well as, the other stakeholders should be executed to make the e-waste management process eco-friendly. It is noteworthy that, the strategies, such as, LCA, MFA, MCA, and EPR have proved itself to be competent in resolving the detrimental issues associated with e-waste management. Every tool utilized in e-waste management possesses distinct characteristics and features that differentiate them from one another. For instance, LCA offers several benefits in supporting e-waste management. LCA enables the estimation of material consumption effects, thereby influencing the development of eco-designed products. Additionally, LCA facilitates the evaluation of both environmental and economic aspects associated with the EoL disposal of electronic devices. On the contrary, MFA is utilized to explore the flow of e-waste materials, estimating waste generation, and its proper recycling or disposal. This strategy is widely used in developing territories like, China, India, where larger recycling plants were established to deal with the e-wastes exported from developed countries. MCA is powerful modelling approach for developing useful strategies, and selecting proper location of establishing recycling plants, owing to environmental and economic benefits. Although, MCA has proved itself as powerful tool for managing hazardous solid wastes, it is widely used in managing e-wastes. EPR is a powerful tool focusing on the responsibility of the producer to take back the e-wastes from the user after being dysfunctional. This EPR strategy is currently being employed in developed, as well as, developing territories like, Japan, Germany, India, Thailand, Netherlands, UK, and USA. However, different countries have modified their EPR policies as per their convenience to make the process suitable for them.

SUSTAINABLE E-WASTE MANAGEMENT

The sustainable management of electronic wastes necessities proper planning and strategies from policymakers around the globe [105]. The strategies should include proper utilization of existing technologies, easy and economically viable procedure, minimization of environmental pollution, and consumer awareness. The advanced technologies for recovering metals from e-waste, such as, pyrometallurgy, hydrometallurgy, bio-metallurgy should be included in the sustainable waste management procedures. The key challenge in the electronic waste management lies in the collection of different electronic waste materials from different sources and their proper segregation. One interesting study by Forti et al. [19] suggests, out of the total electronic wastes generated globally, only 17.4% were collected while the rest 82.6% were remained as abandoned. This fact suggests significant lacunae in the policies of e-waste management. Thus, the success in the sustainable e-waste management lies in the sincerity and responsibility of each and every stakeholder associated with it. Government should take initiative to make proper guidelines for consumers, manufactures, traders, and recyclers. Proper regulatory body should also be there to supervise each step of management and ensure proper recycling of e-waste materials to maintain environmental serenity. Local bodies can play an important role in the collection and segregation of e-wastes. Transportation of electronic wastes has always remained a major challenge associated with the indefinite amount of e-wastes from different cities. To get rid of the associated hazards, the electronic wastes from developed countries are transferred to developing countries, where the legislation related to electronic wastes are flexible and thus the electronic wastes are informally treated leading to severe damage to the eco-system. Sustainable transportation of electronic wastes can only be reached by developing proper channel of collection and transferring the segregated wastes to the respective recycling stations. All the stakeholders, viz. manufacturers, consumers and recyclers play vital role in the smooth operation of the e-waste management. Figure 7 represents a schematic approach for sustainable e-waste management.

CIRCULAR ECONOMY (CE) AND SUSTAINABLE DEVELOPMENT GOALS (SDGS)

The informal and unlawful management processes of e-waste management are creating significant damages in the human health and environment. The deterioration in the economy is also evident associated with the conventional practices of e-waste management. The traditional methods like, landfilling and thermal treatment is very much unlikely in terms of economic aspects as it led to severe damage in the economy associated with significant loss in terms of transportation and labour. However, the proper sustainable strategies may lead to inhibit environmental hazards along with escalating circular economy (CE). In addition, it creates several job opportunities along with suppression of health and ecological hazards in the developing countries [108]. Numerous devel-

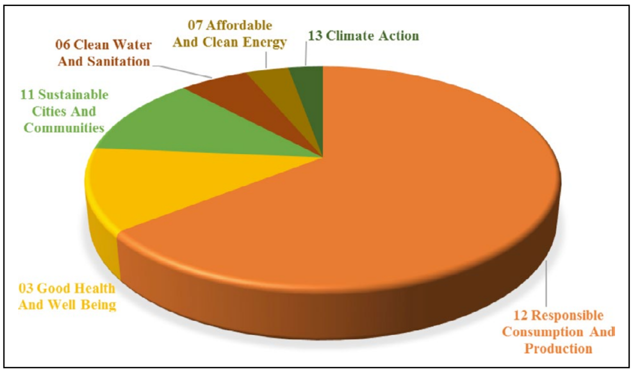

Figure 8. Sustainable development goals, expected to be achieved by the sustainable e-waste management.

oping nations have well-established and dynamic repair and refurbishment industries that could benefit from additional assistance and support through international development initiatives to maximize their capabilities [109]. International development programs have the potential to provide further support to developing countries in maximizing the growth and professionalization of their existing vibrant repair and refurbishment sectors.

The sustainable strategies of e-waste management may also help to attain nine sustainable development goals (SDGs) out of the seventeen SDGs as targeted by UN for 2030 (Fig. 8). The SDG 12, i.e. "Responsible Consumption and Production" appears to be the most achieved SDG, owing to the importance of awareness and behavioural setup of consumer, as well as, EPR policies in dealing e-wastes. The well-planned management strategies for sustainable development of the environment would favour "Good Health and Well-Being" as specified by SDG 3. In addition, the systematic, sustainable e-waste management practices are expected to favour "Sustainable Cities and Communities" i.e. SDG 11. The systematic e-waste management can also evoke "Clean Waste and Sanitation" as specified in SDG 6. The systematic e-waste management policies can again lead to "Affordable and Clean Energy" and "Climate Change" as targeted in SDG 7 and SDG 13, respectively. The unlawful disposal of the components of electric cars, as well as, silicon wafers from solar panels can be a secondary cause for climate change. The sustainable strategies of e-waste management can thus favours in restricting any change in climate associated with e-wastes.

CONCLUSION

The modern civilization, as well as, technological advancements is growing the amount of e-wastes generated globally. The statistical data suggests an e-waste generation of 59.4 Mt in 2022 and is expected to be reached 74.7 Mt in 2030. The European continent is found to recycle the highest amount (42.5%) of e-wastes, whereas, USA being a developed territory found to recycle <10% of its e-wastes generated. With rapid population growth, as well as, technological advancement, the generation of e-wastes is increasing day by day and has become a fact of emergent concern for scientific and research communities worldwide. Though the most developed territories generate the highest amount of e-wastes, little efforts has been put towards managing them. European countries, including UK, Germany, and France are managing significant amount of e-wastes responsibly. The bibliometric parameters associated with the e-waste management research suggest growing research interest of the worldwide research community in managing e-wastes. China found to contribute the highest number of articles in the era of e-waste management followed by USA and India. In addition, significant research focus has been put in the detrimental effects of e-wastes, recovery of heavy and precious metals from e-wastes, processes and policies associated with systematic e-waste management. The informal and unscientific management of e-wastes led to severe health and environmental hazards. The traditional waste management methods, such as, landfilling, and incineration expels significant amount of heavy and toxic chemicals to the environment, leading to severe air, water, and soil pollution. However, proper management strategies for e-wastes not only inhibit the associated harmful effect towards the lives on earth, but also favour circular economy. Strategies like, LCA, MFA, MCA, EPR displayed good potentiality to deal with the e-wastes after EoL. The sustainability of the strategies for managing e-wastes lie in the responsibility of all stakeholders associated with it. Additionally, the sustainable e-waste management is expected to fulfil several SDGs as targeted by UN for 2030.

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DATA AVAILABILITY STATEMENT

The author confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

USE OF AI FOR WRITING ASSISTANCE

Not declared.

ETHICS

There are no ethical issues with the publication of this manuscript.

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