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REVIEW ARTICLE

Concepts of circular economy for sustainable management of electronic wastes: challenges and management options

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Abstract

The electronic and electrical industrial sector is exponentially growing throughout the globe, and sometimes, these wastes are being disposed of and discarded with a faster rate in comparison to the past era due to technology advancements. As the application of electronic devices is increasing due to the digitalization of the world (IT sector, medical, domestic, etc.), a heap of discarded e-waste is also being generated. Per-capita e-waste generation is very high in developed countries as compared to developing countries. Expansion of the global population and advancement of technologies are mainly responsible to increase the e-waste volume in our surroundings. E-waste is responsible for environmental threats as it may contain dangerous and toxic substances like metals which may have harmful effects on the biodiversity and environment. Furthermore, the life span and types of e-waste determine their harmful effects on nature, and unscientific practices of their disposal may elevate the level of threats as observed in most developing countries like India, Nigeria, Pakistan, and China. In the present review paper, many possible approaches have been discussed for effective e-waste management, such as recycling, recovery of precious metals, adopting the concepts of circular economy, formulating relevant policies, and use of advance computational techniques. On the other hand, it may also provide potential secondary resources valuable/critical materials whose primary sources are at significant supply risk. Furthermore, the use of machine learning approaches can also be useful in the monitoring and treatment/processing of e-wastes.

Highlights In 2019, ~ 53.6 million tons of e-wastes generated worldwide.

Discarded e-wastes may be hazardous in nature due to presence of heavy metal compositions.

Precious metals like gold, silver, and copper can also be procured from e-wastes.

Advance tools like artificial intelligence/machine learning can be useful in the management of e-wastes.

Keywords Electronic wastes · Environmental health · Recycling and recovery · Circular economy · Sustainable development goals

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Introduction

E-waste can be defined as unwanted, not working, or at the end of the useful life of any equipment which operates on an electromagnetic field and electrical currents (UNEP 2007). It conceals wide ranges of electronic devices, varying from hefty domestic appliances to equipment used in ITs and telecom sectors. It also encompasses appliances from the medical, automobile, sports, and toy sectors (Li et al. 2007; Chen et al. 2015). Different parts of electric and electronic equipment (EEE), like used batteries, electric wires, printed circuit boards (PCBs), plastic casings, cathode ray tubes (CRTs), poly(p-phenylene terephthalamide, activated glass, and lead capacitors, are also categorized as e-waste (Lambert et al. 2015; Ilankoon et al. 2018; Mazrouaa et al. 2019). The material design of EEE is very complex, as 69 elements from the periodic table can be found in EEE, including precious metals (like platinum, gold, rhodium, silver, copper, iridium, ruthenium, and osmium), Critical Raw Materials (CRM) (like indium, cobalt, bismuth, palladium, antimonyand germanium), and noncritical metals, such as iron and aluminum. Figure 1 shows the proportions of different types of metals which are expected to be present in e-wastes.

From Fig. 1, it is clear that categories of precious metals can be procured from the e-wastes including gold, silver, and copper. Due to the speedy evolution of technology and the rising need of consumers all over the world, there is enhanced consumption of natural resources which ultimately leads to greater production of electronic waste (Mmereki et al. 2016; Dhir et al. 2021). In 2019, e-waste generated global sales hit a record 53.6 MT, but only 17.4% was collected and recycled and it is growing up environmental concerns over the large volumes of e-waste. An enormous loss of recyclable material resources has always forced for developing an effective obsolescence management strategy that specifically targets e-waste to combat inappropriate

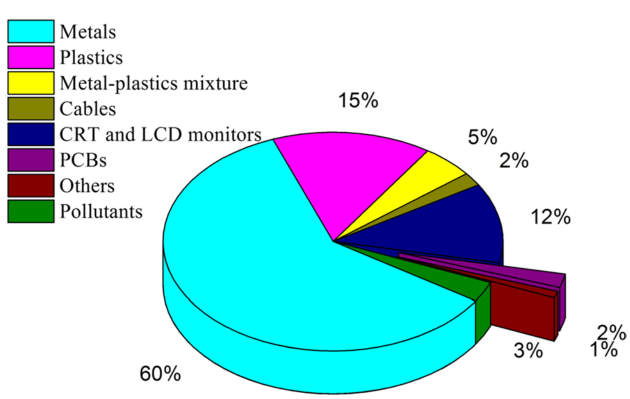

Fig. 1 Generalized material composition in e-waste [data sources: Ongondo et al. (2011) and Mmereki et al. (2016)]

practices such as dangerous landfill or home storage (Deng et al. 2023). In most developing nations, especially low-income and middle-income nations, a major fraction of e-waste is unscientifically getting disposed over landfill sites and it is not good for public health. Kuang et al. (2023) reported children-related health disorders due to waste recycling in China. Similarly, recycling e-waste in an informal way is also broadly accomplished. The plastic of wires is used to get burnt directly in the atmosphere for the recovery of copper. Similarly, for the extraction of valuable metals like palladium, gold, platinum, and silver from electronic equipment, the use of acid and extraction process are the commonly practiced methodologies in countries like China, India, Pakistan, and Vietnam. In countries like Nigeria and Ghana, e-waste is getting handled unscientifically by adopting a basic methodology to recuperate precious metals. People involved in these services neither have the amenities to protect themselves nor the environment. At present, India having the second largest population is among the top 4 countries for e-waste generation in the world (Forti et al. 2020; Arya and Kumar 2020). Figure 2 shows per-capita e-waste generation in different developed as well as developing countries.

From Fig. 2, it is visible that in developed countries, e-waste generation is very high as compared to developing countries. In 2019, globally, 53.6 MT of e-waste was generated and this quantity may be exceeded up to 74 MT in 2030 and close to 59.4 MT by 2022 (Forti et al. 2020). Over the past decades, this worldwide rapid growth of e-waste has become a major area of concern and its immediate solution is requisite at this time (Dhir et al. 2021). In the present era, due to improvements in lifestyle and progressive evolution in technology, the use of electronics and electrical appliances in day-to-day life has enhanced manifold. These electrical and electronics equipment has become an essential and integrated part of our daily life, and we cannot imagine our life without them. The malicious metals used in these appliances are not only toxic to human beings, but also to the atmosphere which leads to grave consequences. Day by day, the problem of e-waste is increasing as the volumes of e-waste are being generated and the content of both toxic and valuable materials is also increasing (Babu et al. 2007). The "Solving the E-waste Problem (StEP)" initiative forecasts that the world will produce 60 MT or 33% more e-waste by 2022. Asia's leading producer, China, produces about 12.2 MT of e-waste, followed by the USA with 13.1 MT (Forti et al. 2020). A report related to e-waste by the Associated Chambers of Commerce of India (ASSOCHAM) found that e-waste is growing at a compounded annual growth rate of about 25% in India (Garlapati 2016). In India, Mumbai is on the top with 1.2 MT in e-waste generation annually followed by Delhi (0.98 MT/year) and Bangalore (0.92 MT/year) (Kumar and Dixit 2018; Srivastava

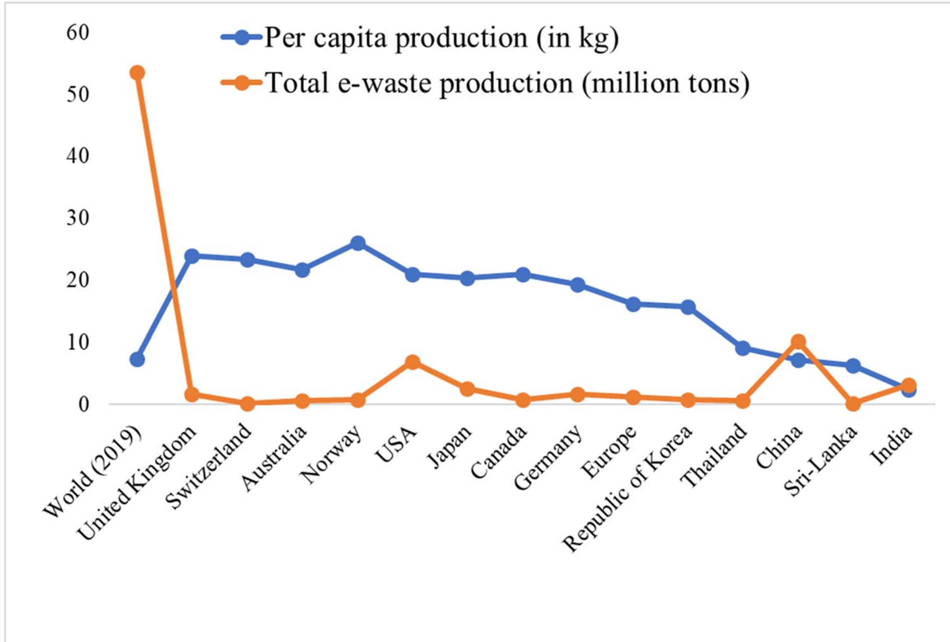

Fig. 2 E-waste generation/capita in some countries (data sources: Ilankoon et al. 2018; Islam and Huda 2020; Tutton et al. 2022)

and Pathak 2020). In today's world, the electronic market is among the most growing sectors in developing countries. There is also prompt financial growth due to an increase in demand and consumption of electronics products. This speedy progress of the electronic sector is also due to rapid urbanization, the quick transformation of technologies, the price drop of electronic goods, and the replacement of old electronic goods with new ones. This gigantic growth in the production of electronic gadgets also results in a colossal upsurge of hazardous electronic waste (Dwivedy and Mittal 2010). Improper handling of these wastes will not only cost for the exhaustion of resources but also causes serious environmental and economic crisis (Menikpura et al. 2014; Brindhadevi et al. 2023; Shi et al. 2023). Particularly in developing nations, proper handling and disposal of e-wastes is still a major area of concern. It is estimated that Brazil generated 2.2 MT of WEEE, i.e., 9.1 kg/capita in 2019. This is less than Mexico's generation rate (1.2 MT) and Canada (0.77 MT) but it is more than the USA (6.9 MT) in Northern America (de Souza et al. 2016). Figure 3 shows the generation of e-waste in different continents, along with their utilization.

Based on Fig. 3, relatively European countries are on the top in the generation of e-wastes as well as their reuse than other continents. Seitz (2014) studied the current e-waste management practices in 10 countries and observed that the management of e-waste is a major area of concern among these nations. It has also been found that there is very little awareness among people regarding jeopardy associated with human health and the environment due to the mismanagement of e-waste (Ikhlayel 2018). D'Adamo et al.

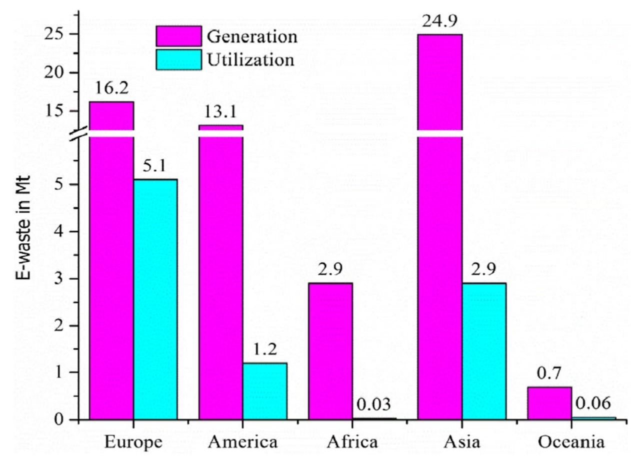

Fig. 3 Generation and reuse of e-wastes in different continents (data source: Global E-waste 2020)

(2022) found that among the waste management practices, the highest priority was given to e-waste management especially for electrical and electronic equipment and discarded vehicles. But, society is more inclined to manage municipal solid wastes only. Most of the environmental problems lie within human behavior; therefore, by changing our behavior towards the environment and with the help of innovative technologies, environmental sustainability can be achieved (Parajuly et al. 2020). For resource sustainability, electrical and electronic products (e-products) are a key area of concern as they may retain many types of rare earth metals (Breivik et al. 2014; Habib et al. 2015). As per the current pattern of increasing e-waste volume, it is expected to get doubled by 2045 (Parajuly et al. 2020). E-waste requires cautious treatment as it is composed of precious resources and noxious elements. E-products became abundant in day-to-day life, but their disposal is still far behind the proper scientific methodologies. This causes potential risks to the resource and negative impacts on the environment as well as human health (Wang et al. 2016; Taneja et al. 2021). As per the global e-waste monitoring report 2020, India is the only country in Southern Asia that is considering legislation with e-waste legislation, although several other countries besides Southern Asia are considering such legislation. Laws to manage e-waste have been already framed in India since the year 2011, mandating that only authorized dismantlers and recyclers collect e-waste. The generation of e-waste in India was 3.23 MT (per capita 2.4 kg) in 2019 (Nisa 2014). However, in India, due to the shortage of proper infrastructure for the management of e-waste, a major chunk of recyclable e-waste is getting disposed of directly to open landfill sites which is a grave threat to humans and the environment (Kumar and Dixit 2018). Singh et al. (2022) analyzed the importance of critical success factors in the designing of an e-waste collection policy in India using the fuzzy DEMATEL approach. Authors found that some critical factors like green practices, technology involvement, certification and licensing, environmental programs, public ethics, and stakeholder awareness of the circular economy are having a major influence on the collection of e-wastes in India. From the perspective of developing nations like India, China, Malaysia, Thailand, and Vietnam, very few studies have been conducted for providing practical solutions in e-waste treatment facilities (Awasthi and Li 2017; Milovantseva and Fitzpatrick 2015; Shumon et al. 2014; Zhang et al. 2012). In earlier studies, no emphasis has been given to the interrelationship among the obstacles affecting the execution of e-waste management (Kumar and Dixit 2018). Reduce, Reuse, Recycle (3Rs) is a technology platform that connects markets to promote a circular economy and aims to encourage consumers to dispose of their e-waste. In developed countries, high priority is given to e-waste management, whereas, it is difficult for developing countries to fully adopt or replicate e-waste management in developed countries and many related problems, including a lack of investment and skilled human resources. Furthermore, the lack of infrastructure and inappropriate laws for e-waste management. In addition, there is another shortcoming which is the lack of awareness about the roles and responsibilities of stakeholders and institutions involving e-waste management etc. In the present paper, emphasis has been given to provide information for the effective management of the e-wastes through a meticulous literature review so that concepts of sustainable development goals and circular economy can be attained. Extractions of precious metals and the possibilities of developing a business venture using e-wastes have also been discussed. Moreover, it would be a great effort to conserve the environment along with social health protection.

Types of e-wastes and their possible sources

Different types of e-wastes are being generated in the environment. Possible sources of e-wastes may be our homes, IT industries, automobile industries, medical sector, and other electrical and electronic materials. There are 10 categories of e-wastes as per the European regulatory bodies of e-waste management (Garlapati 2016). Discarded e-wastes may cause severe problems as they may contain many harmful inorganic and/or organic contaminants. Some common categories of e-wastes such as computer accessories, toys, Internet materials, air conditioners, automobiles, microwave ovens, refrigerators, lamps, washing machines, phones, and printers have toxic heavy metals which are very harmful. In chips and batteries and medical and laboratory instruments, persistent organic contaminants and electrolytes and X-ray and radioactive chemicals are used respectively. Many harmful effects can be caused by these e-wastes (Kofi Adanu et al. 2020), and the advancement in technology, less life span of a material, and policy change are among the most responsible reasons for the generation of e-wastes (Amankwah-Amoah 2016). However, harmful materials may include toxic heavy metals like lead, mercury, chromium, and persistent organic contaminants (Ilankoon et al. 2018).

Methodology adopted to write this review paper

The relevant research papers, book chapters, conference papers, websites of regulatory bodies, and government reports were collected from different electronic databases which are very authentic for writing this paper. Usually, the research papers (journals and conferences) were accessed from Science direct, Pubmed, Springer, Taylor & Francis, Google scholar, etc. as depicted in Fig. 4. Moreover, relevant book chapters and books were also searched for the same.

The title and framework of the paper were decided on the basis of different types of keywords such as e-waste-related problems (for example, environmental concern, social health), sustainable development goals, concept of circular economy in e-waste management, expected challenges, future scope, and application of machine intelligence. Management of e-waste was the central focus during the paper writing. It also ensured to evaluate all the critical factors such as recent publications, novelty and cost-effective methods of e-waste management, application of computational tools, and possible green processes. It was the brainchild of all the co-authors who were also involved in

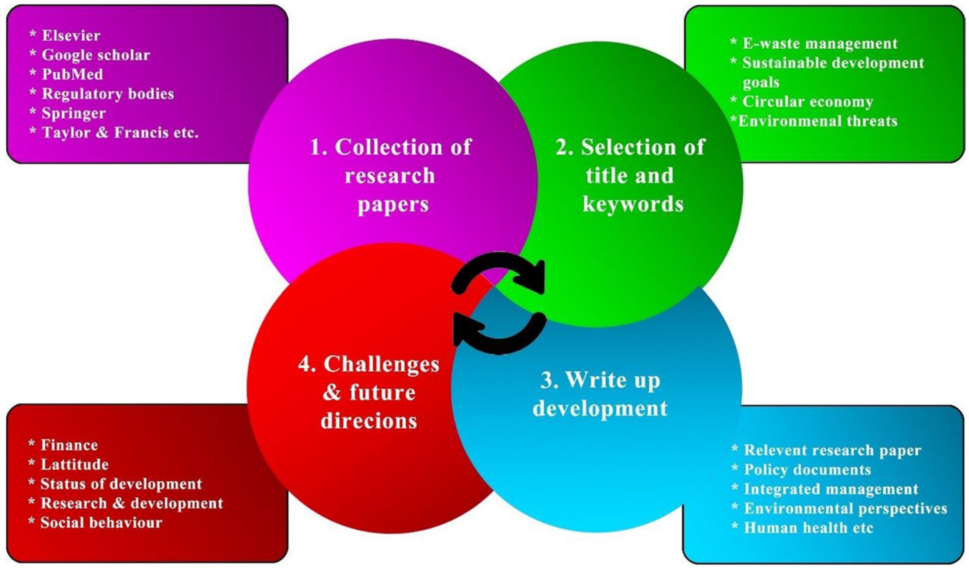

Fig. 4 Adopted frameworks for writing present review paper

the brainstorming during the writing of this paper to ensure the maximum possible quality.

Impacts of e-wastes on human health and environment

Discarded e-wastes can cause many harmful impacts on the environment and human lives, if they have been mishandled such as chronic health disorders and environmental degradation (in terms of air, water, and soil contaminations) (Amankwah-Amoah 2016). Some specific section is illustrated in the following sections regarding e-waste-induced problems.

Impact on the environment

E-waste leads to environmental contamination including water, air, soil, and other biota afterwards, mainly due to poor disposal activities. E-waste disposal sites and recycling centers are reported releasing heavy metals and particulate matters into the environment (Chatterjee 2008). Substances liberated from e-waste have been categorized into two types; hazardous and non-hazardous. Hazardous substances include heavy metals, polycyclic aromatic hydrocarbons, poly dibenzofurans, brominated diphenyl ethers, and polychlorinated dibenzo-p-dioxins, whereas non-hazardous substances include metals Cu, Se, Pt, and Ag among others (Awasthi et al. 2016; Zeng et al. 2014; Zhang et al. 2013). Both the categories of pollutants released from e-waste cause ill effects on the environment and human health when their presence is above the permissible limits. The impacts of e-waste depend on the age of the specific e-waste, and hence, it varies for the same type of e-wastes. Recycling is a process in which pollutants are removed or delayed, but the large quantity of e-waste still causes the accumulation of enormous amounts of pollutants in landfills and the environment. Developing countries like India, Nigeria, Pakistan, and China use unscientific methods for e-waste recycling which releases heavy metals and other recalcitrant pollutants into the environment (Pradhan and Kumar 2014; Sthiannopkao and Wong 2013). Release of these hazardous contaminants into the environment gets easily associated with various processes like bioaccumulation, contamination of food, and widespread exposure to ecological processes and hence causing widespread risk (Sepúlveda et al. 2010; Chan and Wong 2013; Chen et al. 2011).

Impact on air quality

Several types of e-waste contaminants get dispersed as dust or fumes into the air. Ingestion, inhalation, and skin absorption are all primary routes of exposure in human beings (Mielke and Reagan 1998). Children and infants are considered to be the most susceptible to e-waste mishandling because of a high frequency of breathing, high chances of in utero-exposure, frequent breast-feeding, extreme hand-to-mouth activity, frequent food intake, and low efficiency of toxicants removal rate (Guo et al. 2012; Xu et al. 2012, 2018). Various hazardous primary e-wastes including Hg, Pb, Cd, PCBs, and other secondary e-waste toxicants, including PAHs, dioxins, and difurans, are produced in the environment during the processing and recycling of e-waste at Guiyu, China; Agbogbloshie, Ghana; the National Capital Territory (NCT) region, India; Shershah (Karachi), Pakistan; Lagos, Nigeria; and Dhaka, Bangladesh (Sthiannopkao and Wong 2013). However, the presence of contaminants in the surrounding atmosphere may vary depending upon the type of work that is performed in the nearby area. For example, recycling and dumping sites which are often associated with electrical components are responsible for the release of substantial quantities of Pb and Cu into the atmosphere (Brigden 2005). The atmosphere acts as a mediator for the dispersion of these metals from one place to another place as these contaminants can stay for a long time and also can travel for greater distances (Brigden 2005). These metals are suspended in the form of particulate matters and also get deposited to the soil surface and open water resources and, hence, can be bio-accumulated in the lives of water, soil, and plants and will cause serious ill effects on the consumption of contaminated water or food product.

Impact on water quality

Waste effluents are also responsible for water pollution as reported in many studies too (Awual et al. 2019; Awual 2019). Many studies have been carried out recently on the removal of different types of heavy metals and toxic dyes from water (Awual et al. 2015, 2016, 2020; Awual 2015; Naushad et al. 2019; Khandaker et al. 2021; Yeamin et al. 2021; Kubra et al. 2021; Hasan et al. 2021; Teo et al. 2022). Contaminants from e-waste enter into the aquatic environment, both into groundwater and surface water via leaching and dissipating processes from electrical and electronic equipment dumping industries and other e-waste-related activities. A study performed by Luo et al. (2011) had suggested that poly brominated diphenyl ethers (PBDE) level in the sediment samples from the Nanyang River near Guiyu town had increased significantly and they also reported that carp from this river has great potential to bioaccumulate. According to a study conducted by Wu et al. (2008), on snakes, top predators present in an aquatic environment nearby an e-waste recycling plant consumed ~ 1091 ng/g PBDE and 16,512 ng/g PCBs on a wet weight basis. A study on water flow from downstream areas in Pearl River Delta had shown an elevated level of PBDE and PCBs (Luo et al. 2009). Besides PBDE, brominated flame retardants namely decabromodiphenyl ethane and1, 2-bis (2,4,6-tribromophenoxy) ethane, etc. were reported in down streams of Pearl River Delta (Shi et al. 2009). According to a study reported by Dharini et al. (2017), water resources present in the nearby area having e-waste recycling and detention facilities do not fulfill the general water quality standards in terms of pH, total dissolved solids, hardness, chlorides, and conductivity.

Impact on soil health

In recent decades, the sudden increase in human activities leads to the release of certain amounts of hazardous contaminants into the soil and hence causing pollution in farmland soil as well (Zhang et al. 2015). Waste recycling plants are considered one of the prime sources responsible for the contamination of soil mainly due to the release of metals and other contaminants in higher concentrations. However, the management of e-waste by using primitive methods has become one of the most problematic reasons for e-waste contamination of the soil (Awasthi et al. 2016). Plants, soil, and snails of Guiyu town were reported to have a higher concentration of PCBs and PBDEs (Liu et al. 2008). Luo et al. (2011) reported that the burning of metallic chips and electric circuits is one of the reasons for elevated metals like Cd, Cu, and Pb in soil. Luo et al. (2009) reported a higher value of PBDE in agricultural soils within 2 km of range from an e-waste recycling workshop. In another study, soil from the same range was reported to have high concentrations of polychlronateddibenzo-p-dioxins and dibenzofurans (PCDD/Fs), PCBs, and PAHs (Shen et al 2009). Several soil samples studied from the area of the e-waste recycling center in India located at Loni were found to have extremely high metal concentrations. Almost all of the soil samples examined were beyond their permissible levels, with the highest Pb content (~ 174 times greater) than the guidelines. Apart from that, excessive amounts of Cd, Hg, Cr, and Zn have been identified in this region also (Link 2014; Weerasundara et al. 2020). Plant roots can easily assimilate the harmful toxins including heavy metals present in the soil and transmit them to various parts of the plant including stem, leaf, and fruit. Hence, e-waste-contaminated soil is considered one of the major sources of crop and vegetable contamination (Meng et al. 2014).

Impact on the human health

Improper handling, processing, and application of poor recycling methods related to e-waste pose life-threatening impacts on human health (Orlins and Guan 2016). Exposure to hazardous substances released from the e-waste can enter the human being either via ingestion, inhalation, or dermal contact (Awasthi et al. 2018). Workers associated with e-waste handling or recycling have high chances of direct occupation exposure mainly due to a lack of safety measures (Chen et al. 2011). E-waste exposure identification is very complicated due to variety of exposure sources, routes, exposed individual characteristics, including body weight, age, sex and immunological status, and non-identical time periods of exposure (Alabi and Bakare 2017). Contaminated water, air, soil, and food are the main reason for the widespread risk associated to e-wastes in humans (Vaish et al. 2020). Children may have greater risks after having exposure to the e-wastes present in their surroundings or food items (Pronczuk-Garbino 2005; Kuang et al. 2023). As humans get exposed to e-waste contaminants, hazardous substances will be released into the human body and stored in fatty tissues and pose severe threats to human health (Liu et al 2018). Metals can enter the body of a human either by inhalation, ingestion, or dermal contact. Oral exposure includes the consumption of water and food contaminated with e-waste (Zheng et al. 2013; Fu et al. 2008). It has been found that heavy metal gets exposed to the human body mainly due to ingestion (90%) (Weerasundara et al. 2020). Heavy metals can also be bio-accumulated into the plant tissues from water resources, contaminated soil, or air deposition (Singh et al. 2010; Bi et al. 2009). Heavy metal–contaminated soil–grown food items are mostly responsible for the increase of heavy metal concentrations in meat-based products (González-Weller et al. 2006). Through a number of studies performed by various researchers around the globe, it had been reported that heavy metal leads to various kinds of disorders in humans, including the nervous system, urinary, cardiovascular, blood, liver, kidney, learning inability, cancer, and urine (Thomas et al. 2009; Bhutta et al. 2011; Yan et al. 2013). Therefore, it is necessary for local bodies and government organizations to perform an assessment study related to risk and exposure in the areas of e-waste processing and recycling. Through reports, it had been found that the e-waste recycling center located at Guiyu in China has led to an increase in the level of dioxins in humans above the recommended maximum limit set by WHO (Chatterjee 2007). The presence of dioxins above than prescribed limit has been found in the sample of human milk, hair, and placentas hence showing that dioxins are entering the human body from water, air, or via foodstuffs further posing serious ill effects (Chan et al. 2007). A study performed by Ha et al. (2009) reported that soil and water from the areas around the Guiyu e-waste recycling center had an elevated level of heavy metals and that poses serious ill effects on workers and residents living in these nearby areas (Chan et al. 2013; Sjödin et al. 1999; Guo et al. 2010; Wu et al. 2010; Huo et al. 2007; Xing et al. 2009; Li et al. 2008). Studies were performed by various researchers related to e-waste in Bangalore, India; China; Ghana; it has been found that the workers and residents were found to be exposed with an elevated level of heavy metal, polybrominated diphenyl ethers, dioxins, polychlorinated biphenyl, etc. (Asante et al. 2012; Zheng et al. 2011; Song and Li 2014; Ha et al. 2009; Alabi and Bakare 2017). Based on the above discussion, it is clear that toxic contaminants present in e-waste items may cause huge toxicity (Table 1), if they are mishandled or discarded openly.

Based on the above discussion, it is clear that toxic contaminants present in e-waste items may cause huge toxicity (Table 1), if they are mishandled or discarded openly.

Management strategies for the e-wastes

Advancement of technology is one of the fast-growing sectors because of the rise in the requirements of the consumer's perception. Consequently, the quantities of e-wastes are increasing day by day across the world (Mmereki et al. 2016; Dhir et al. 2021). E-wastes may contain some hazardous elements such as cadmium, lead, mercury, polybrominated diphenyl esters, etc., and hence, their high rate of generation and mismanagement may create many disturbances to the environment and living entities. Therefore, safe management practices for the e-wastes need to be explored on a priority basis (Awasthi et al. 2016; Garlapati 2016; Kumar and Dixit 2018). Figure 5 shows a general framework of e-waste material (life cycle) since its production to disposal. It can also be correlated with the practices required to achieve the concept of circular economy in which waste materials are used up to maximum resource utilization.

From the above figure, it is apparent that technical advancement and human behavior are mostly responsible for the generation of e-wastes in the society. Moreover, policy formulation and implementation can also play a major role in the management of e-wastes as already are being adopted by some developed nations of the world (Table 2). Table 2 shows some practices of effective e-waste management in four developed countries including Japan, the UK, the USA, and Switzerland.

Based on the above table, it has been observed that better e-waste management can be achieved by inculcating the attitude of taking responsibility by the consumer, retailer, management authorities, and policy makers as well. Furthermore, some e-waste management options are proposed by worldwide researchers as discussed below:

Recovery of precious metals from the e-wastes

E-waste can be a source of income for individuals or industries. For example, in Bangalore (India), around 18,000 MT of e-wastes is generated annually. These e-wastes do have some precious metals like gold, silver, platinum, copper, aluminum, and rare earth metals and these elements can be reused. Furthermore, new commercial benefits from them can also be explored as opportunities (Garlapati 2016; Dias et al. 2018; Dhir et al. 2021; Xavier et al. 2023).

Recycling of e-wastes

Like other wastes, some parts of the e-wastes can also be recycled such as capacitors, circuit boards, and plastics. Energy production is also possible after incineration of the e-wastes as the plastic of the e-wastes a feedstock for

Table 1 An overview of common toxic chemical present in different types of e-wastes and their exposure

Toxic chemicals	Common sources	Human health problems	Environmental problems	References
Polybrominated diphenyl ethers (PBDEs)	Circuit boards, cables, and television sets	Neurological problem posing a serious, deadly health problem, thyroid, fatigue, loss in weight loss, headache, abdominal pain	Soil, air, and water contamination	(Siddiqi et al. 2003; Pacyniak et al. 2007; Shi et al. 2019; Pavithra et al. 2020)
Polychlorinated hydrocarbons	Chips, plastics, and wires	Lung cancer, mutagenic, teratogenicity	Soil and atmosphere contamination	(Pavithra et al. 2020)
Polybrominatedbiphenols	Chip, electric wires, capacitors, transformers	Neurological disorders, cancer, problem related to liver, reproduction, and thyroid	Soil, air, water, and food contamination	(Tharappel et al. 2008; Shi et al. 2019; Pavithra et al. 2020)
Dioxins	Generators, capacitors, transformers, ceiling fans, electric motors, plastics from the computer, and peripherals	Problem related to reproduction, neurobehavioral, and immunity, carcinogenicity, mutagenicity, teratogenicity	Air, dust, food, water, soil, and atmosphere contamination	(Pavithra et al. 2020)
Lead (Pb)	Cathode ray–based electronic appliances (e.g., monitors, batteries, lamps)	Mental growth retardation among children, disorders to the nerves, kidneys, reproductory organs, etc	Air, water, and soil contamination	(Grant et al. 2013; Ilankoon et al. 2018; Wu et al. 2019; Arya and Kumar 2020)
Cadmium (Cd)	Batteries, circuit boards, semi-conductors, mobile phones, etc	Nephrological, respiratory, bone, reproduction-related problems	Cadmium-laden dust may cause water and soil contamination	(Kumar and Singh 2014; Ilankoon et al. 2018; Gangwar et al. 2019; Arya and Kumar 2020)
Mercury (Hg)	Light-producing devices, circuit boards, thermometers, medical devices, switch, etc	Disorders of the brain, nervous system, renal problems, chronic toxicity, child growth retardation	Mainly water contamination and biological magnification	(Kumar and Singh, (2014; Shamim et al. 2015; Gangwar et al. 2019)
Chromium (Cd)	Corrosion-resistant coatings etc	Carcinogenicity, health effects on newly born babies, endocrine and reproductive disorders	Soil health and groundwater contamination	(Quinteros et al. 2008; Wu et al. 2019)
Nickel (Ni)	Batteries, cathode ray–based electronic appliances	Carcinogenicity of lungs, heart disorders, mental retardation in children, etc	Soil and water contamination	Li and Achal (2020)
Antimony (Sb)		Damage lung, heart, liver and kidney, eye irritation, and hair loss	Air, water, and soil contamination	Kumar and Singh (2014)
Bismuth (Bi)	Or dermal contact	Kidney damage, serious ulceration stomatitis, albumin or other protein substance in the urine, diarrhea, skin reactions, serious exodermatitis	Air, water, and soil contamination	(Kumar and Singh 2014; Wu et al. 2019)
Lithium (Li)	Lithium ion–based battery	Vomiting, stomach problems, fatigue, muscle cramps, etc	Soil contamination	Li and Achal (2020)

Fig. 5 Framework of e-waste from production to disposal along with some management activities

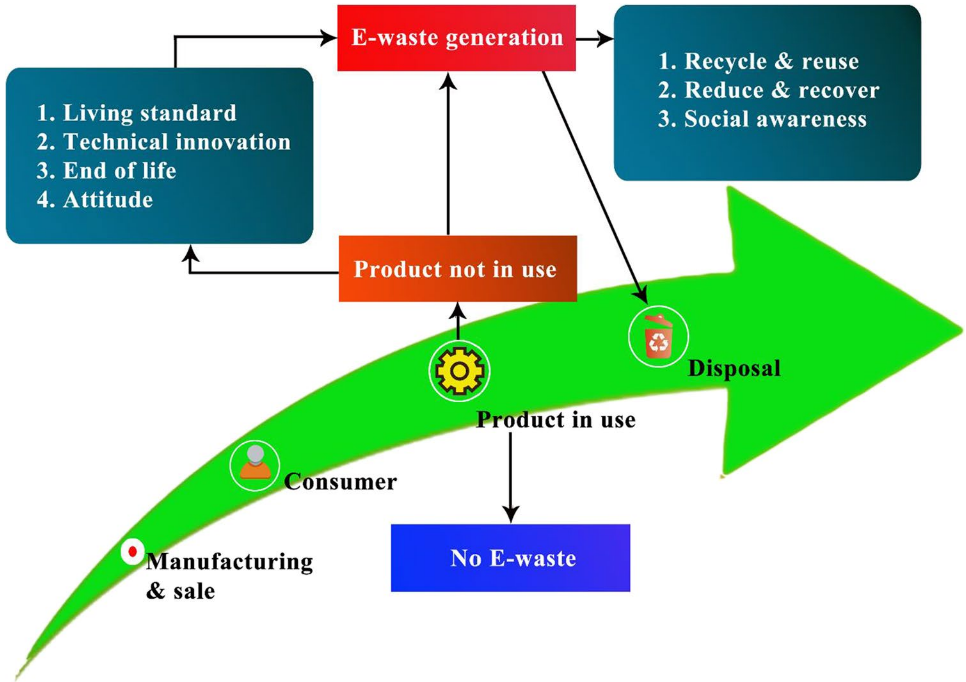

Table 2 Practices adopted in developed countries for effective e-waste management (modified from Ongondo et al. 2011)

Country	Commonly generated e-wastes	Management aspects	Scheme of e-waste management	Effective disposal
Japan	Television sets, air conditioners, washing machines, refrigerators; computer accessories	With the help of retailers	Extended producer responsibility, provision of recycling fee	About 80% send to developing country
The UK	Discarded household electronic materials	Through the cooperation of customers and distributors	Extended producer responsibility	
The USA	Television sets, cell phones, computer accessories	Municipal authorities, voluntary services	Extended producer responsibility, provision of recycling fee	
Switzerland	Different types of electrical and electronic devices	Different Swiss organizations	Extended producer responsibility	
Australia	Television sets, laptops, computer accessories	Different Australian organizations	Extended producer responsibility	Council drop-off Centers (20%)

pyrolysis (CII 2006). However, it will require extra setups for controlling toxic emissions (CII 2006).

Thermo-chemical approaches to generating energy using waste materials have attracted researchers across the world as it is also helping in the recycling of waste materials (Garlapati 2016). Additionally, new materials can also be manufactured from the recovered materials from the e-wastes (Baxter et al. 2016) as the prime objective of recycling is to procure worthy materials so that the threats to the environment and human health could be avoided. Furthermore, recycling may also create several opportunities for the society in terms of employment, business, etc. (Schluep et al. 2009). As per the studies of the United Nations University (2017), recycling e-waste would be beneficial for environmental conservation as well as society. However, people's attitudes, knowledge, and behaviors are very important issues to determine the accomplishment of proper recycling as well as management of e-wastes (Echegaray and Hansstein 2017; Kumar 2019).

Arya and Kumar (2020) have found that India has taken many steps regarding the better management of its e-waste items as shown in Fig. 6.

However, Indian authorities and citizens still need to do a lot regarding every environmental problem including waste management (municipal, electronic, plastic, hazardous, etc.). Recycling waste materials (including e-wastes) is one of the best practices to manage them. It can be achieved by using them as either developing building materials or some other valued products through a process or material alteration (Garlapati 2016). Furthermore, recycling e-wastes

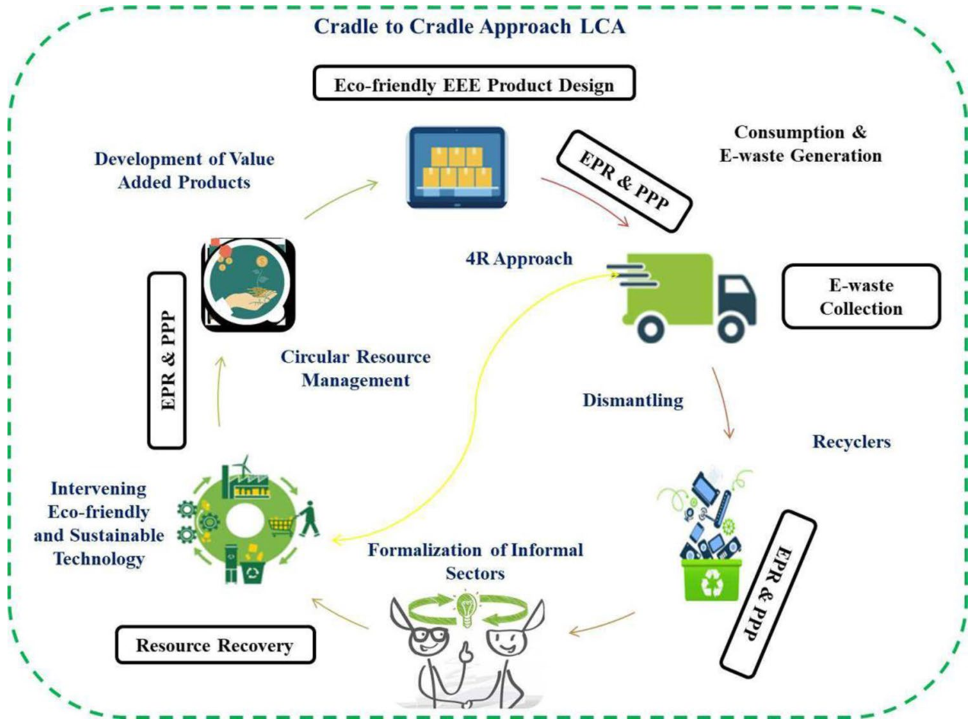

Fig. 6 An Indian integrated approach for e-waste management (source: Arya and Kumar 2021: Reprinted from Arya, S., Kumar, S. (2021). E-waste in India at a Glance: Current Trends, Regulations, Challenges and Management Strategies. Journal of Cleaner Production, https://doi.org/10.1016/j.jclepro.2020.122707 with permission from Elsevier)

can also reduce the chance of secondary contamination in the different ecosystems. Therefore, it is recommended to develop an efficient collection, storage, transportation, processing, recovery of value-added products, treatment, and safe disposal of the e-wastes at local as well as national levels in consultation with regulatory bodies (Cucchiella et al. 2015). Furthermore, de Souza et al. (2016) observed that recycling and recovery of precious metals present in the e-wastes could be beneficial options to reduce their harmful impacts on the living world along with restricting burden on the landfills. Moreover, such practices will be helpful in the generation of employment and maintaining environmental safety guidelines as it may also discourage mining along with less emissions of greenhouse gases. Therefore, it can be inferred that recycling and recovery of wastes could also be helpful to cope with global warming and ultimately climate change.

Microrecycling concept for recycling of e-waste

Metal recovery from e-waste is an attractive opportunity of business for private enterprises and transportation of bulk materials of such waste would create high costs. Microrecycling units for material recovery can be established in smaller areas (around 50 m^2) using small cost. The microrecycling concept deals with the collection and segregation of e-waste materials from local communities at small-scale factories which helps to reduce the cost of transportation, consumption of raw materials, saving of fossil fuels, and environment same time able to produce value-added recycled materials for further use (Sahajwalla and Hossain 2020). These microfactories have various processes including microrecycling units for obtaining materials using the process of fractional heating and separation of various metals, polymers, and ceramics from e-waste. Furthermore, enabling multiple reactions using selective thermal transformation to obtain vigilant separation of valuable metals and alloys. Recently, it has been found that valuable materials can be obtained via novel and fundamental pathways including the generation of metals, metal nanoparticles, alloys, and nanoceramics from the e-waste (Singh et al. 2021a, b). The main purpose of this concept is to process and recycle e-waste efficiently, safely, and sustainably at a smaller level which would be able to supply value-added materials for the utility of nearby industries.

Development of the effective policies for e-waste management

Effective policies have always been a remarkable tool to achieve success in many disciplines. If we take the example of India, e-waste management in its early stage as the country did not have effective policies, despite being a great manufacturing hub of electronic devices (Borthakur and Singh 2020; Garlapati 2016). However, the Indian environment ministry (i.e., MoEFCC-Ministry of Environment, Forest and Climate Change) has issued some guidelines for the effective management of e-wastes (Arain et al.

2020). Indian decision-makers have developed many waste management rules/guidelines between the years 1989 to 2016. In 2009, first-time e-waste handling rules were drafted, whereas in 2011, e-waste rules were provided along with plastic waste rules. In India, e-waste management–related policies are not well developed, and hence, it requires serious revision to provide safety for both the environment and human health (Garlapati 2016). But, it requires rigorous revisions for the effective management of e-wastes (Kumar and Agrawal 2020). Similarly, China has also formulated many waste management policies but most of them are focused on municipal solid waste management (Jin et al. 2021). European Union (EU) in the early 2000s had performed an important role in setting the guidelines to regulate e-waste management after the debates raised in the 1989 Basel Convention. The waste electrical and electronic equipment (WEEE) Directive of 2002 was the first important regulation in order to establish targets to ensure the recycling, recovering, and treatment of these types of waste (Isernia et al. 2019; Stonewell 2013). This directive in Europe was used for further elaboration of different legislations in the next years (Lopes dos Santos and Jacobi 2022). This directive was further used for developing national legislation in countries like Canada, the USA, Japan, and Australia (Bandyopadhyay 2008; Gough 2016; Kumar et al. 2017). Bibliometric studies can also be helpful in the development of fruitful policies for a particular subject as reported by Taneja et al. (2021) in the waste management discipline. Recently, Grab et al. (2023) and Asokan et al. (2023) stated that principles of extended producer responsibility could be a better option for e-waste management, if implemented in the framing of e-waste management policies and executed for the recycling and collection of the e-wastes.

Imparting professional training to the workers of waste management authorities

Waste management is a multi-functional process as it involves processing, use of instruments, safety measures, monitoring, supervision, etc. Hence, trained manpower could be a great asset for waste management authorities because these skilled persons can play significant roles in the management of wastes (Gaidajis et al. 2010; Heeks et al. 2014). Different types of stakeholders can be involved in the training for successful waste management including academic institutes, research organizations, ministries, municipalities, local public, technical persons, etc. (Srivastav and Kumar 2020; Arya and Kumar 2020). A similar hierarchy can also be followed for effective e-waste management including regulatory bodies, government organizations (local and national), non-governmental organizations, corporate world, society, etc.

Imposing heavy fines to the violators

A heavy fine may be imposed on the violators of waste management. The provision of the penalty should be elaborated by the regulatory authorities for all the stakeholders. The responsibilities of every stakeholder (individuals, institutions, industries, etc.) should be defined well so that it can be implemented honestly and efficiently. Furthermore, rules can be made very strict especially for the violators of e-waste management as it may have some dangerous elements too. Examples follow.

Rewarding with lucrative incentive to the best performers by the waste management authorities

Apart from imposing fines, there must be a provision of rewarding incentives to the best-performing firms, societies, institutions, or industries by the regulatory bodies on the basis of annual waste audit report. Therefore, it will create some positivity among the different stakeholders of the waste generators and their management (Ravindra et al. 2019). Cucchiella et al. (2015) reported that NGOs and manufacturers need to be encouraged for the different activities (collection, storage, recycling, etc.) related with e-waste management at different administrative levels.

To ensure the concepts of circular economy in waste management

Recently, the assimilation of concepts of circular economy (Ellen MacArthur Foundation 2019; Parajuly et al. 2020) and sustainable development goals are among the important objectives for every organization/institution. According to Sauvé et al. (2016), recycling of the materials and maximum resource recovery from wastes should be ensured to restrict future environmental pollution. Meaning, thereby, maximum use of the materials must be ensured to reduce waste generation (Ellen MacArthur Foundation 2019) and it can be achieved by adopting eco-friendly technologies and green policy developments as well as inculcating fruitful innovative corporate cultures (Ghisellini et al. 2016). Figure 7 is the representation of the concepts of circular economy in e-waste management.

Figure 7 shows that environmental and economical sustainabilities can be achieved in waste management in any nation/region after following the concepts of the circular economy. The above practices (mentioned in the figure) can be adopted to achieve better e-waste management through the concept of circular economy and sustainable development goals. However, wise consumption of the materials

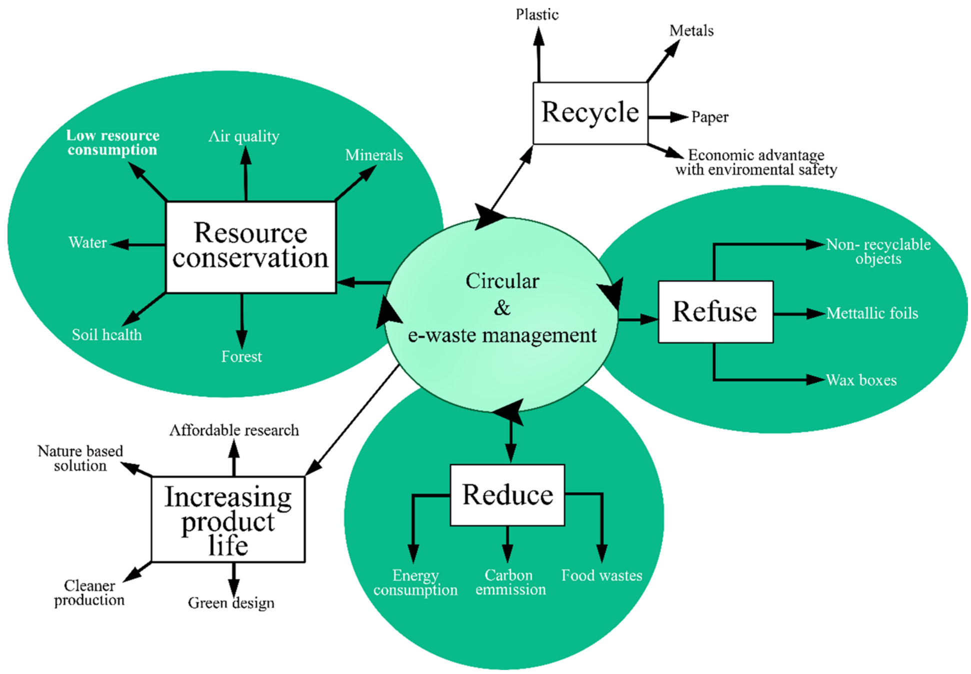

Fig. 7 Concept of circular economy to be followed for effective e-waste management

may depend on awareness, behavior, lifestyle, morality, culture, environmental ethics, psychology, etc. (Knussen and Yule 2008; Parajuly et al. 2020).

Role of machine intelligence techniques in e-waste management

The discarded electronic devices are generally termed e-waste (Bhutta et al. 2011; Mor et al. 2021; Umair et al. 2016). There is a serious concern regarding the unsafe handling of these devices (Bhutta et al. 2011; Mor et al. 2021; Umair et al. 2016). It may cause harm to human health and the environment as these scraps may contain cadmium, lead, beryllium, zinc, etc. (Bhutta et al. 2011; Mor et al. 2021; Umair et al. 2016). Several works have already been done by researchers in the domain of disposal and the management of e-waste but the challenges are so many. Awasthi et al. (2016) discussed the rapid growth in e-waste. They observed that the common methods of dealing with e-waste like acid baths and open burning may release furans, dioxins, and other heavy metals which may lead to harmful effects on the surroundings. Figure 7 shows a layout of artificial intelligence–based e-waste management system. All the information relevant to e-waste has been gathered and transferred to the cloud server. The cloud server matches the gathered e-waste sources from the existing database. The database category based on the review has already been maintained on the cloud server. The components from the e-waste product have been separated based on the classification. The automated machine learning–based category advisor can be capable of the classification of the components (Vimala et al. 2022; Thakur et al. 2022; Dubey et al. 2021). The components are then filtered and the IoT devices will accept the filtered component and provide a name and send an alert message to the server. It is already attached to the server for the demand of the individual component. It can be synchronized with the received e-waste resources. IoT-enabled devices help in the product assignment and set it in the cloud server with the updated product list. So, any request for these sources can be fulfilled properly from the server automatically. The machine intelligence approaches will be helpful in the reassignment, automation, and learning from history. So that the detection of the reusable components will be improved automatically. It will be helpful in gathering, filtration, and reusability and improving product usability based on the automated guidelines of the model.

Rahman et al. (2020) studied waste management. They have proposed an architecture for waste management based on deep learning and the Internet of Things (IoT). They devised a smart trash bin concept with multiple sensors. For data monitoring purposes, IoT and Bluetooth technology have been used. They achieved the convolutional neural network (CNN) accuracy of 91.3% and 86% of the system usability scale (SUS). Agarwal et al. (2020) studied the growth of e-waste. It has been discussed in terms of developing economies. They have reviewed and analyzed the artificial intelligence prospective in the literature from 2015 to 2020. They found that the computational technique may be helpful in the segregation of e-wastes. Kang et al. (2020) analyzed e-waste management in terms of precious base metals and found that smart e-waste collection management can be done by using smart techniques. Their approach has the automatic notification and scheduling of the e-waste management mechanism system as it was developed in Malaysia. Senthilselvi et al. (2020) studied the impacts of technological development in the case of e-waste worldwide. They have suggested the challenges in the disposal of electronic equipment. Their aim was to provide automation in metal purification measurement by the use of machine learning techniques. For the metal separator from the mobile phones, they used magnetic separation, eddy current, and pyro-metallurgical and hydrometallurgical processes. The noise removal from the images of the extracted metal was performed by CNN. It is helpful in feature extraction and classification. For validation from the learned features, they used and rectified linear units. They successfully extracted the metal which can be used in any other manufacturing process. Singh et al. (2021a, b) studied the disposal of e-waste. They proposed an IoT-based collection vendor machine for e-waste management. It was associated with the QR code for the related information. It contains the alert system based on the capacity (threshold point) along with the secure disposal technique. Chen et al. (2021a, b) discussed e-waste in terms of a tremendous increase in environmental issues due to the toxic substances that can adversely affect health as well as the environment. They proposed an artificial intelligence technique for the smart analysis of hazardous components. Abou et al. (2021) analyzed the growing need for automated e-waste recycling and management. They used AlexNet layers for e-waste sorting and management. Yu et al. (2021) discussed the challenges in waste disposal. They have discussed the mechanism of reducing, reusing, recycling, and recovering. They have proposed an automated artificial intelligence framework. Their framework was capable of specific information gathering, planning, and management. Li et al. (2021) utilized the machine learning technique in e-waste management. They used a gradient-boosting regression tree and neural network for the monitoring of urban sub-segments. The arrangement was improved based on machine learning techniques with an exactness of 99.1%. Islam et al. (2021) discussed teleworking. They suggested that teleworking has increased the generation of e-waste. They mainly focused on the collection of metals. The recovery was performed based on gravity, density, and integrated approaches. Aswani et al. (2021) suggested that in the current Indian scenario e-waste is a huge problem. They have suggested machine learning techniques to handle the recycling procedure of metals from the e-waste. Ramya et al. (2021) studied an advanced waste managing scheme based on long-range (LoRa) protocol and the TensorFlow framework. The communication protocol was managed by LoRa. Object detection was performed by the TensorFlow framework. It performs actual time object detection. The TensorFlow framework was used for actual time object detection and organization of waste data. Radio-frequency identification (RFID) was also used for the identification of e-waste. Khan et al. (2021) discussed the role of machine learning and IoT in e-waste collection. For effective e-waste management, they proposed an approach using machine learning and IoT. They used an Arduino UNO microcontroller, ultrasonic sensor, and moisture sensor. Their main aim is to measure the dumping ground waste index. Elangovan et al. (2021) studied the increase in e-waste. They used deep learning for the classification of the metal present in e-waste.

The major challenges found are as follows:

1. There are different levels of challenges in e-waste management like collection, extraction, reusing, and recycling based on the extracted patterns.
2. There is the need for applicability of machine intelligence methods based on the requirement levels.
3. There is the need for a hybrid framework with integrated approaches for the purpose of analysis, extraction, feature engineering, labelling of e-waste, automation of devices without human interference, and alert system with enhanced connectivity.
4. There is also the need for data handling mechanisms to achieve cost savings, flexibility, quality control, and data storage, increase collaboration, and automate software updates.
5. There is also the need for automated control flow in all levels.

A framework has been proposed as shown in Fig. 8, to fulfill the abovementioned challenges. Our suggested framework is divided into four parts:

1. *Optimized data collection and processing*: in the present framework, cloud computing has been used for data collection and processing. This phase is responsible for surveying, monitoring, reporting, and notification system on e-waste. It accepts the request for e-waste collection from different users using mobile applications. It is responsible for the data gathering, identification, and other details like the requester, and information on the e-waste products including the metal and reusable components.
2. *Machine intelligence approaches:* in this phase, machine intelligence approaches like machine learning, deep learning, and machine vision approaches can be used for the purpose of analysis, extraction, feature engineering, labelling, and classification with the approach automation.
3. In the third phase, an IoT-based e-waste container has been proposed for handling the sensing and notification mechanism based on the collected data. This framework is also capable of filtering reusable components along with the precious metal.

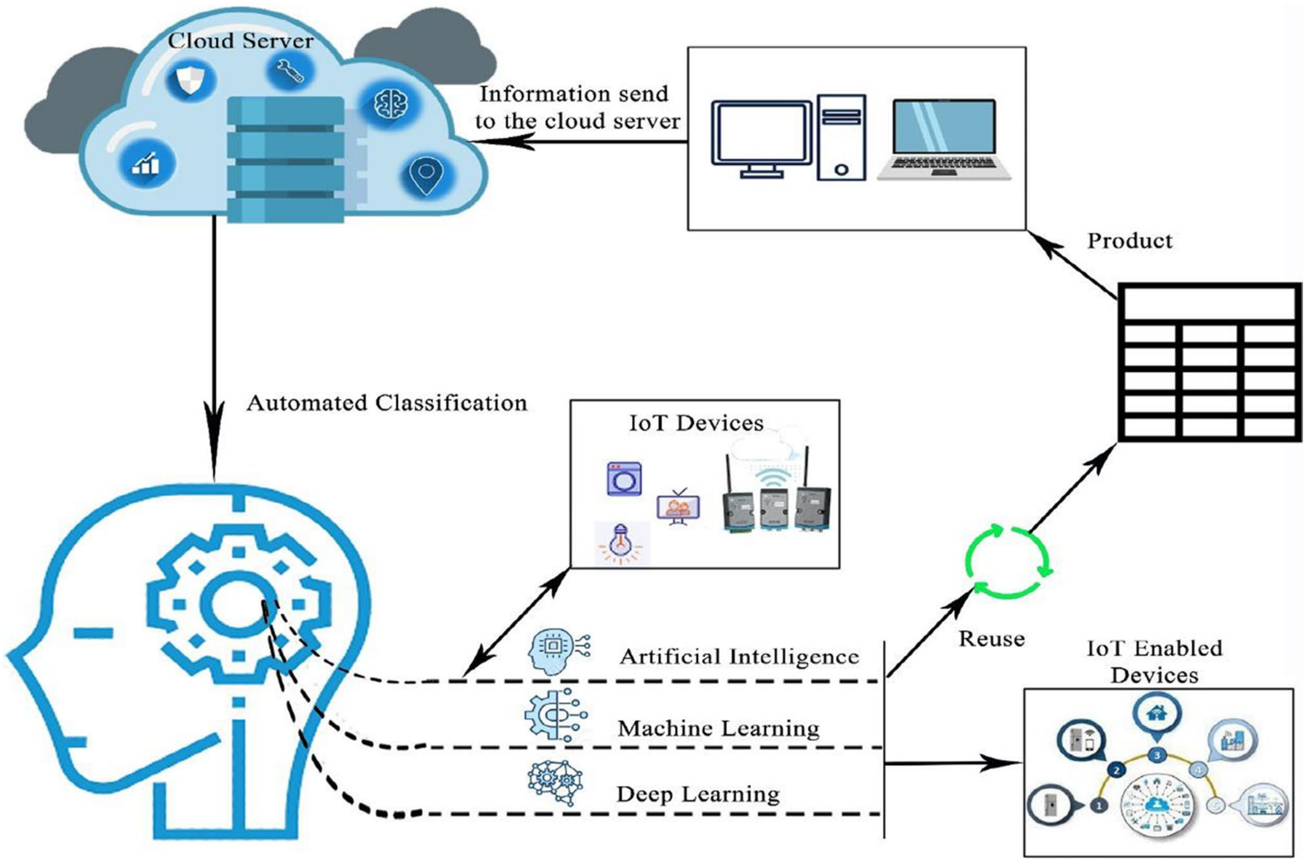

Fig. 8 Framework for e-waste management based on machine intelligence approach

4. The final phase is the automated notification for the requestor, if any need arises for the components received initially.

The above framework is capable of handling e-waste management in an efficient way in accordance with proper reuse and recycle mechanisms.

Miscellaneous recommendations for effective e-waste management

It is highly recommended that the concept of 4Rs (reduce, reuse, recycle, and recovery) must be entertained in e-waste management practices for a better future. In Spain, a well-illustrated recycling procedure was developed to manage e-wastes so that it can reach the suppliers after being discarded by the consumers (Queiruga et al. 2012) and such type of frameworks may be one of the best practices to endure maximum recycling of electronic waste products. Non-measurement of e-waste generation (as a separate account) is not being effectively implemented so it has been observed as a major hurdle for e-waste management. Hence, for effective management of the e-wastes at individual as well as municipal levels, it should ensure to develop an inventory containing harmful impacts on the environment and living creatures (Debnath et al. 2016). For better e-waste management, some common recommendations may be emphasized such as:

- Public awareness (especially among consumers) about the negative impacts of e-waste on the environment and human beings and also their guidelines (Garlapati 2016)
- Introducing fees for recycling purposes (Garlapati 2016)
- Mandatory segregation of the e-wastes from the domestic wastes at the individual level.
- Endeavors should be made to limit the use of electronic/electrical appliances up to the maximum extent or their lesser use should be encouraged. For example, a paperless provision in banks/offices may reduce the application printers along with saving papers.
- Exploring the possibility of digitalization in every system (e-governance), especially traditional systems.
- Monitors of computers should be energy-efficient so less consumption of energy can be ensured.
- Electronic appliances should be switched off, when not in use.

- Electronic parts of the computers (or any electronic devices) should be reused, if possible based on their life and condition.
- Research activities should be increased for better e-waste management.
- Eco-friendly electronic appliances should be developed as reported by Asus—a reputed company in Taiwan (Debnath et al. 2016).

For e-waste management, basically, two approaches are under practice in developed and developing nations. In developing nations, normally, e-wastes are not under proper recycling, and moreover, their proper disposal is also not being followed. Furthermore, developing countries are also involved in the extraction of precious metallic content from the e-wastes imported from the developed nations (Manhart 2011). Hence, it seems that sustainable management of e-waste could be achieved through developing proficient techniques for e-waste recycling, providing specialized training to the workers, and devising powerful policies. Furthermore, the policies, responsibilities of administration, waste management authorities, and electronic appliances manufacturing industries must be defined and monitored regularly (Esenduran et al. 2019). For example, since the year 2003, in Switzerland, the roles of production units and importing industries have been set to follow e-waste management guidelines as described in the policies namely Extended Producer Responsibility as well as the Advance Recycling Fee (Sinha-Khetriwalet al. 2005). Furthermore, Japan has also developed Consumer Pays model in which users can give back electronic gadgets (supposed as waste) to the retailers along with prescribed fees (Widmer et al. 2005). Similarly, the US Environmental Protection Agency (USEPA) is responsible for the better management of the e-wastes generated in the country under National Electronic Action Plans (Gaidajis et al. 2010). Some developing nations are also trying to manage their e-wastes like Peru which initiated sustainable approaches to e-waste management by developing skills to collect followed by recycling the same for protecting human beings and the environment. Columbia was able to recycle ~ 185 tons of cell phones generated from 30 cities during 2007–2014 (Kofi Adanu et al. 2020).

Anticipated challenges during e-waste management

Apart from the availability of the above management practices, there are many challenges that may come on the ground during e-waste management. If we take the example of Europe, most of the population is well aware of the wise use of resources and also knows that their exploitation is not good for the environment (European Union, 2014). Moreover, people claim that they are well involved in waste segregation, reuse, and also earning revenues from the wastes (Europeet al. 2018). Similarly, developing countries (China, Malaysia, Thailand, and India) are importing e-waste from the Organization for Economic Co-operation and Development (OECD) group of countries in the name of manufacturing and reuse (Kumar and Dixit 2018). Furthermore, social acceptance is another issue regarding the reuse and development of business models using e-wastes (van-Weelden et al. 2016). To ensure the proper recycling of the e-wastes, behavior of the individual person and right decision are also having a direct impact (Parajuly et al. 2020).

Furthermore, some commonly observed challenges faced by the management authorities regarding e-waste management include a lack of guidelines, negative public perception, lack of green initiatives, financial constraints, and inadequate infrastructure.

These challenges (as shown in Fig. 9) may be a lack of citizen's knowledge about recycling (Godfrey et al. 2013; Kumaret al. 2016), no adequate guidelines (Chaturvedi et al. 2007; Wath et al. 2010), non-implementation of green initiatives (Ravi and Shankar 2014), financial crisis (Kumar and Dixit 2018), inadequate infrastructures of collection and recycling (Kumar et al. 2017), confusion among the producers and consumers regarding accountability (Manomaivibool and Vassanadumrongdee 2011; Kiddee et al. 2013), etc. Moreover, we are living in a digital age and the world is observing technological advancement at an unprecedented rate. The durability of electrical and electronic equipment (EEE) has decreased tremendously simply because of the frequent hardware and software up-gradation. Globally, this trend is contributing a voluminous amount of waste electrical and electronic equipment (WEEE) or e-waste. Studies predict that the total volume of e-waste will cross 74 million tons by 2030 as it is increasing at the rate of 3–5 percent per annum. China (10.1 MT/year), the USA (6.9 MT/year),

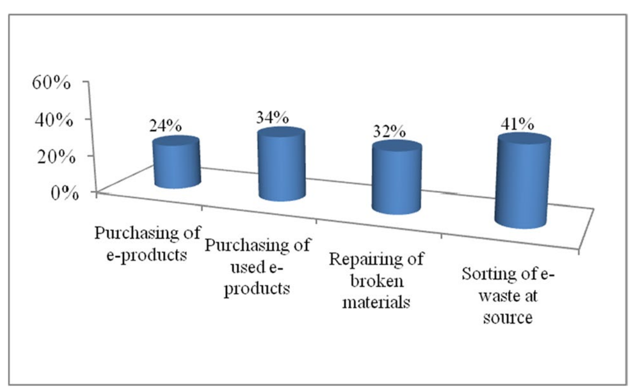

Fig. 9 Actual gap in the claim and practice of European people (data extracted from Parajuly et al. 2020)

India (3.2 MT/year), Japan (2.1 MT/year), Germany (1.6 MT/year), and Brazil (2.1 MT/year) are the biggest producers of WEEE (Andeobu et al. 2021; Shittu et al. 2021). E-waste is adversely affecting the biotic and abiotic components of the environment. Hence, in order to achieve the UN sustainable development goals (SDGs), circular economy and resource recovery, and efficiency, standardized and effective e-waste management procedures are indispensable. Materials present in the WEEE have been classified into five categories viz. ferrous metals, non-ferrous metals, glass, plastics, and other materials by different workers (Shittu et al. 2021). Scarcity and recovery of resources (minerals, rare earth metals, heavy metals, polymers, etc.) and energy are other dimensions which the globe is observing with the exponential rise in the manufacturing of electronic products. The biggest challenge before the world is to design and adopt standardized recycling procedures. Researchers suggest that only a small fraction of the e-waste is recycled by organized sectors (having required expertise and infrastructure) while a large chunk (nearly 82 percent) is tackled by the informal sector which creates environmental and occupational health hazards. China, India, and Ghana can be considered the hub of informal e-waste recycling while countries like Australia, Japan, and Canada have skilled workforce and infrastructure to scientifically recycle the waste (Rautela et al. 2021). Studies have suggested e-waste urban mining to effectively tackle the problem and emphasized the issues and challenges related with it. Urban mining helps in the recovery (rare earth metals, plastic and polymer, heavy metals, etc.) and recycling of e-waste in a phased manner (mechanical separation, hydrometallurgy, and pyrometallurgy), which in turn boost up the circular economy. However, in developing countries like India, there are serious challenges associated with urban mining, mainly the lack of coordination and integration between thee-waste collectors, dismantlers, recyclers, etc. (Ikhlayel 2018; Sharma et al. 2021). Due to this un-coordinated and unskilled approach, a huge volume of e-waste gets treated and discarded using different informal methods like dismantling and incinerating in open. Also, a large fraction of e-waste goes to landfill sites which is again a hazardous practice in the long run. The role and application of artificial intelligence, machine, and deep learning should also be explored in e-waste management (Chen et al. 2021a, b).

However, the actual scenario is quite different from people's claims as the gap in the claim and practice of European people (Parajuly et al. 2020) is shown in Fig. 9.

Therefore, based on the above graph, a general opinion may change as can be seen in the case of European society (being considered one of the most civilized societies).

Discussion

In the future, the focus should be given to spreading awareness among the local citizens (or all the stakeholders) to change their behavior so that e-waste management or any other environmental crisis can be overcome easily. Thus, it appears that principles of circular economy can be significantly ensured up to a maximum extent after public participation. Knowledge of relevant technologies, economical issues, principles of circular economy, and environmental concerns should also be discussed together as it may increase the better output in the recycling/reuse of goods (Makov et al. 2018). It has also been observed that environmental ethics, laws, and education have significantly elevated the consciousness of environmental protection among the public (Solomon 2010). Some prescribed amounts of money can also be paid by the consumers without any force; however, it may vary according to gender, wedding conditions, convenient recycling process, and the toxicity of the e-wastes (Saphores et al. 2012). In India, e-waste management is not an easy task because of knowledge gaps regarding environmental conservation and recycling processes along with incompetent policies, financial issues, etc. (Jindal and Sangwan 2011). Economical profit and societal acceptance can assist in better e-waste management after coordinating with all the stakeholders. Furthermore, strict laws and policies can also play significant roles in e-waste management (Ravi and Shankar 2014; Kumar and Dixit 2018). Similarly, there are no any legal frameworks in African countries for the recycling of e-wastes. However, they are good at reusing (~85%) electronic or electrical devices and it is around 2–3 times more in comparison to rich countries. Australia has a well-defined provision for recycling television and computers with the collaboration of government regulatory authorities and industries. China, India, Japan, South Korea, and Taiwan are the only Asian countries who have formulated e-waste management policies. However, Taiwan is at the top with 82% e-waste recycling, whereas Japan and South Korea have achieved 75% e-waste recycling. In other countries of the world, policies regarding recycling and standard development are not adequate (Garlapati 2016). Hence, other countries need to develop proper policies particularly for appropriate e-waste management. Most importantly, employment generation through developing business modules can also be performed using e-wastes as these wastes can be used for the production of fuels (energy) through pyrolysis and procurement of precious metals like gold, silver, platinum, copper, and aluminum, and are reusable (capacitors, circuit boards, plastics, etc.), and recyclable materials (CII 2006).

For effective and efficient management of high volumes of e-waste, they need to be addressed on a priority basis. A few of the challenges and tangible measures are given below:

- Creating awareness about the hazardous impacts of e-waste and recycling of the same.
- Accurate and real-time measurement and quantification of e-waste being generated.
- Developing a skilled workforce and expertise to transform an unorganized recycling sector into an organized one and create a new organized recycling setup.
- Developing a state-of-the-art infrastructure where e-waste can be recycled with minimum environmental and health hazards.
- Incentivizing the recycling sector by incorporating various economic and financial tools like easy loaning to create recycling infrastructure, tax relaxation, extended producers' responsibility, and public–private partnership (PPP).
- Develop materials and technologies so that maximum recovery can be done after recycling.
- Recovery of resources and energy is a crucial aspect which can be achieved via urban mining.
- Informal and unscientific methods should be immediately checked.
- Frequent monitoring and stringent policy should be adopted in order to mitigate any adverse impact on the environment.

Recent events showed that the organized and informal sector related to e-waste management has been severely affected by unprecedented and unalarmed situations like the COVID-19 pandemic outbreak. Therefore, policy formulators should consider such challenges also. Moreover, the feasibility of advance computational tools may also be explored especially for e-waste management so that it can be beneficial for the environment and public health. Cost–benefit analysis of the available techniques of e-waste management should be carried out appropriately which can provide a better direction for future studies.

Conclusion

Worldwide, large amounts of e-waste are produced as a result of purported modernization efforts. These e-wastes may also include some harmful elements in addition to certain valuable and recyclable items. Therefore, their careless handling and open disposal practices could also be harmful to the environment and biosphere. E-waste is frequently mismanaged since the general population is ignorant about their importance and also degrees of threat. Radioactive substances may also be present in e-wastes which can damage the plant tissues and ultimately inhibit plant growth. Radioactive materials in the soil can hinder the uptake capacity of the plants for nutrients. Apart from awareness, lack of responsible consumption and infrastructure facilities, financial crisis, etc. are also some major challenges to effective e-waste management. However, some good practices can reduce the levels of these challenges which include motivation of society, change in behaviors, availability of adequate funds/incentives, proper availability of e-waste management facilities, and adoption of green practices. The application of advanced computational tools is also playing crucial roles in multiple disciplines, and hence, better e-waste management practices can also be done by using techniques like artificial intelligence and machine learning. Furthermore, economic feasibility can also be maintained by applying such approaches. Moreover, it will also help in the achievement of many sustainable development goals either partial or complete along with accomplishing the concepts of a circular economy.

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