Chapter 12
E-waste and Their Implications on the Environment and Human Health

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Abstract Rapid influx of modern technology in the past few decades has led to an exponential increase in the usage of the electrical and electronic equipment on a global level. This unprecedented increase, on one hand, has revolutionized the field of communication and information technology, providing a major boost to business and economic activities; however, it has also led to the generation of one of the fastest-growing waste streams in the world, popularly referred to as E-waste. Constituents of E-waste are both hazardous and nonhazardous and valuable, comprising of toxic elements (Cd, Cr, Hg, As, Pb, Se), radioactive active substances, halogenated compounds (polychlorinated biphenyls, polybrominated biphenyls, polybrominated diphenyl ethers, chlorofluorocarbon, etc.), plastics, glass, ceramics, rubber, ferrous and non-ferrous metals (Al, Cu) and precious metals like Au, Ag, and Pt. With 20–50 million tonnes of global E-waste generation and an anticipated growth of 33%, the problem of rapidly growing E-waste is an issue faced by both developed and developing countries of the world. Additionally, unscientific and crude disposal and recycling practices for management of E-waste have severe

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A. Khan et al. (eds.), *E-waste Recycling and Management*, Environmental Chemistry for a Sustainable World 33,
https://doi.org/10.1007/978-3-030-14184-4_12

implications for the environment and human health resulting from release and exposure to toxic emissions and constituents. In view of the above, the present chapter attempts to provide a brief insight on the global trends of E-waste generation, critical issues and challenges associated with E-waste and its effects on environmental and human health, thereby highlighting the need for sustainable environmental management of this newer waste stream.

Keywords E-waste · Heavy metal toxicity · Environment · Human health · Sustainable waste management

12.1 Introduction

Technological revolution and advancement in the field of the electrical and electronic equipment are unprecedented in the present twenty-first century. Evidently, the developed nations of the world use more than 900 different types of electronic and electrical goods and gadgets (Huisman et al. 2012). Tremendous growth in the electronics market resulting from higher consumer demand and relatively short useful life of equipment/gadgets especially personal computers, laptops, tablets, smartphones, television sets, kitchen appliances, etc. has led to generation of a newer and bigger waste stream comprising of outdated electronic goods popularly referred to as E-waste, i.e. Electronic waste (Wong et al. 2007; Nnorom and Osibanjo 2008; Dwivedy and Mittal 2010). With the growth rate of 4% per year, the world currently generates nearly 50 million tons of E-waste annually, making it one of the fastest-growing streams of solid waste (UNEP 2005; Wang et al. 2013). According to an estimate, more than 130 million computers and television sets become obsolete in the USA on an annual basis. During the years 1997–2007, more than 500 million computers in the USA and around 610 million till 2010 in Japan were discarded (Bushehri 2010). E-waste is a complex category of solid waste containing both valuable and hazardous substances such as plastics, precious and non-precious metals (Au, Ag, Pd, Pt, Fe, Cu, Al, etc.), Pb-containing glass, Hg, Cd-containing batteries, toxic organics, flame retardants and chlorofluorocarbons (Wang et al. 2012). Improper handling and management of E-wastes may result in loss of resources and also cause environmental damage (Table 12.1).

Burgeoning amounts of E-waste generation and its hazardous constituents, trans-boundary movement and disposal issues have aroused significant environmental concerns worldwide and especially in developing countries pertaining to their growing consumption rates and imports from developed nations. Nearly 80% of the electronic goods or E-waste rejected from the developed countries on account of being old and less eco-friendly is carried across the developing nations (Hicks et al. 2005). Lack of proper legal framework and policies regarding safe disposal of imported E-waste in developing countries of Asia and Africa further intensifies the problem with serious implications to the environment and human health (Kiddee et al. 2013). Unregulated and primitive techniques of E-waste recycling such as

Table 12.1 Comparing E-waste generated and heavy metal concentration between India, China and Nigeria

	India	China	Nigeria
E-waste generated	1.7 Mt	6.0 Mt	0.22 Mt
Rate of recycling	5%	34.6%	ND
Air	Cr, 18; Mn, 59.6; Cu, 111; Zn, 191; Mo, 81.6 ng/m^3	*Mechanical workshop*: Cr, 0.554; Cu, 27.76; Cd, 0.108; Pb, 12.34 mg/g (manual)	ND
		Workshop: Cr, 0.436; Cu, 31.80; Cd, 0.398; Pb, 02.043 mg/g	
Water	*Waste leachate*: Al, 1315; Cd <1; Cu, 185; Ni, 9; Pb, 4; Zn, 17 ppm	*Well*: Cd, 5.60; Cr, 0.058; Cu, 112; Mn, 138; Ni, 3.07; Pb, 1.37	*Well*: Pb, 1.8; Cd, 0.006; Zn, 0.84; Cr, 0.25; Ni, 1.23
Soil	*DS*: Cr, 73; Cd, 2.33; Cu, 592; Mn, 449; Pb, 297; Zn, 326	*DS*: Cd, 52; Cr, 2.51; Cu, 107; Mn, 1.01; Ni, 2.52; Pb, 111; Zn, 5.40	*DS*: Pb, 502; Cd, 7.82; Zn, 66.9; Cr, 32.65; Ni, 84.24
	RS: Cr, 54; Cd, 0.47; Pb, 126; Mn, 619; Zn, 129; Cu, 429 μg/g	*BS*: Cd, 195; Cr, 3.45; Cu, 413; Mn, 1.12; Ni, 2.89; Pb, 115; Zn, 5.40	
Human health	Cr, 0.29; Mn, 1.16; Cu, 23; Zn, 141; Mo, 0.041; Ag, 2.1 μg/g	As, 0.282; Cd, 0.209; Cr, 1.16; Cu, 10.2; Mn, 1.03; Ni, 0.812; Pb, 2.98 mg/g	ND

Adapted from: Awasthi et al. (2016)
ND no data, *DS* dumping site, *RS* recycling site, *BS* burning site
(a) Balde et al. (2015), (b) Ha et al. (2009), (c) Jha et al. (2011), (d) Wu et al. (2015), (e) Wang et al. (2009), (f) Fang et al. (2013), and (g) Olafisoye et al. (2013)

dismantling, burning, roasting, melting and acid bath are hugely popular in the illegal workshops and factories in the developing countries because of their operational ease and low cost (Ren et al. 2014). These processes/methods, however, contribute immensely to the pollution of surrounding aquatic and terrestrial ecosystems and atmosphere (Fu et al. 2008). Emission or formation of highly toxic metals (Cr, Cd, Pb, Hg, Li, Be, Ba, etc.) and pollutants like polyhalogenated organics including polychlorinated biphenyls, polybrominated diphenyl ethers, polychlorinated dibenzo-p-dioxins and dibenzo-furans occurs during recycling of E-waste and causes pollution of the ambient environment (Wang et al. 2005; Sharma et al. 2018). In a study conducted by Liu et al. (2008), soil, biota and plant samples from an E-waste recycling site in South China showed contamination with significantly higher levels of polychlorinated biphenyls, polybrominated diphenyl ethers and polychlorinated dibenzo-p-dioxins and dibenzo-furans as compared to control sites. Sjödin et al. (1999) also found significantly higher levels of polybrominated diphenyl ethers in the serum of workers at E-waste recycling factories. Adverse effects of E-waste recycling are evident on human health also. Constant exposure of workers and local inhabitants to the toxic chemicals at these sites leads to their bioaccumulation in the body tissues and biomagnification through the food chain (Wong et al. 2007).

12.2 Trends in E-waste Generation

With a largely growing competitive global market of electronic and electrical products and their shorter useful life, E-waste has become a worldwide phenomenon with a growth rate of 5–10% per year (Zheng et al. 2013; Sthiannopkao and Wong 2013). Estimates provided by solving the E-waste problem (StEP) initiative predicted global production of E-waste in the world to rise from 49 million tonnes during 2012 to around 65.4 million tonnes till 2017 (UNU 2013). Higher generation rates and potential hazardous impacts on the environment and human health caused by associated toxic chemicals during recycling and disposal have made sustainable E-waste management a major environmental concern and challenge (Leung et al. 2007; Wu et al. 2008; Luo et al. 2009). Majority of the E-waste from developed world, i.e. the USA, Britain and Europe, is transferred to developing nations like China, India and Nigeria (Chi et al. 2011). E-waste management is an issue dealt differently in terms of policies and methodologies adopted in both developed and developing countries of the world. Developed countries have expensive, fairly regulated and well-devised collection systems, clean recovery technologies such as disassembly stations, and plasma furnaces installed to prevent toxic emissions from E-waste recycling; however still, the majority of the European and North American E-waste remains unrecycled (Barba-Gutiérrez et al. 2008). On the other hand, most of the developing countries (like China, India, Pakistan, Indonesia, the Philippines, Nigeria, etc.) in absence of proper laws, policies and regulatory guidelines resort to primitive, cheap and crude recycling practices such as smouldering, acid baths, crushing, open incineration, etc. at the informal recycling facilities to manage E-waste causing severe damage to the environment and human health (Widmer et al. 2005; Zheng et al. 2013; Yoshida et al. 2016). During the year 2010, developed countries like Japan and the European Union generated 4 and 8.9 million tonnes of domestic E-waste, respectively (Zoeteman et al. 2010), and around 400 million electronic items become obsolete in the USA alone per year. According to Widmer et al. (2005), in the developed countries, E-waste may constitute 8% by volume of municipal solid waste. Receiving more than 70% of the E-waste in the world and also being its second largest producer, China is likely to overtake the USA's E-waste generation by the year 2020 (Hicks et al. 2005; UNEP 2007). It is predicted that by 2030, developing countries will discard approximately 600 million personal computers per year which is twice the number that will be discarded by the developed nations, i.e. 300 million (Yu et al. 2010). In economically advanced Southeast Asian countries like Malaysia and Thailand, E-waste generation was estimated to be 6–10 kg per capita during 2012, whereas it ranged from 2 to 3 kg per capita for middle-income countries like the Philippines, Vietnam and Indonesia (Yoshida et al. 2016).

12.3 Environmental Implication of E-waste

In developing nations, widespread unscientific methods of E-waste recycling have caused severe contamination of soil, water, air and adverse health effects as these products have a high concentration of harmful materials like heavy metals and persistent organic pollutants. E-wastes comprise different materials; most of them are toxicant and cause serious environmental problems (Pant et al. 2012; Chatterjee 2008). Two major kinds of substances are released from E-waste, viz. hazardous (heavy metals, polybrominated diphenyl ethers, polycyclic aromatic hydrocarbons and polychlorinated dibenzo-p-dioxins and dibenzofurans) and nonhazardous (metals like Cu, Zn and Se along with precious metals like Au, Ag, Pt, etc.) (Awasthi et al. 2016; Wei et al. 2014; Zeng 2014; Zhang et al. 2013). Both types of E-waste cause potential harmful impact on the environment if present beyond their permissible limit (Pant 2010). During processing of these E-wastes, a significant amount of toxic compounds are released which causes a detrimental effect on human well-being and the surrounding environment (Robinson 2009; Shen et al. 2009).

Additionally, around 80% of E-waste is illegally transported from advanced to developing nations like India, China, Ghana, Nigeria, and Pakistan because of governmental negligence, lack of stringent policies and lower cost of labour (Pradhan and Kumar 2014; Sthiannopkao and Wong 2013). Several scientists have investigated that workshop sites for processing/transforming of E-waste release toxic substances that contaminate natural surrounding environment (Kwatra et al. 2014; Wu et al. 2014; Stevels et al. 2013). In continuation, many scientists have documented heavy metal contamination in the surrounding environment (water, air and soil) near recycling workshops mainly in developing nations (Leung et al. 2006, 2007, 2008; Wong et al. 2007).

Leaching is the process through which harmful contaminants enter aquatic systems where processed and unprocessed waste may be deposited. Likewise, settling/dissolution of airborne contaminants or hydrometallurgical processes followed by acid disposal penetrate into water or soil thus contaminating soil and aquatic systems. However, e-waste contaminants enter human body via skin absorption, inhalation and ingestion by dust-laden air (Mielke and Reagan 1998). A parallel study by Ha et al. (2009) indicated that dust-laden air near E-waste processing workshops in Bangalore contains contaminants like Sn, Pb, Sb, Cd, In and Bi at a high level of 91, 89, 13, 1.5, 1.3 and 1.0 ng m^{-3}, respectively. Most of the E-waste in developing nations are dealt with little concern often by acid baths and open burning for recovery of a few valuable materials. Result of these processes are harmful contaminants like polybrominated diphenyl ethers, polychlorinated biphenyls, heavy metals, dioxins, furans are observed in surrounding environments, workers and nearby residents. Hence, the environmental impact of the pollutants (polychlorinated biphenyls, polybrominated diphenyl ethers, heavy metals) must be discussed extensively regarding the health and safety of workers or the environment.

12.3.1 Heavy Metal Toxicity

Manufacturing of electronic devices widely uses heavy metals like Cd and Pb in circuit boards and computer batteries, Cu in electrical wiring, etc. (Achillas et al. 2013; Stevels et al. 2013; Zeng et al. 2014). A study done by Morf et al. (2007) found that the average fraction of plastic in E-waste has Pb, Ni, Sn, Zn and Sb at a concentration > 1000 mg kg^{-1} and > 100 mg kg^{-1} for Cd. Primitive processes and techniques are extremely popular in developing nations like India and China. Therefore, it became a new cause of environmental pollution these decades (Chi et al. 2011; Song and Li 2014). The unregulated processing by using primitive techniques like a chemical process, acid baths and burning to procure valuable metals cause severe heavy metal pollution in the terrestrial and aquatic ecosystem (Deng et al. 2007; Wei and Liu 2012).

Additionally, incineration done prior to landfilling increases the mobility of heavy metals, especially Pb (Gullett et al. 2007). In a study by Luo et al. (2011), which collected samples of soils and vegetables from prior incineration sites for heavy metal analysis, the results demonstrated high doses of Zn, Pb, Cu and Cd with values of 3690, 4500, 11,140 and 17.1 mg kg^{-1}, respectively. Also, soils of paddy fields and nearby gardens had a comparatively high level of Cu and Cd. Similarly, the high level of Cd and Pb was observed in inedible parts of vegetables, which goes beyond the maximum permissible limit in China. High doses of Cd, Pb and polybrominated biphenyls were found higher in rice and other crops cultivated near E-waste recycling units. This is because heavy metals are discharged during recovery of precious metals that enter the soils where crops and vegetables are grown by polluting irrigation water or through foliar uptake of heavy metals by air (Bi et al. 2009). Oral intake of contaminated food is an important pathway for translocation of heavy metals from the environment to the human population.

Developing nations like China and India are a hub for recovery of precious metals from E-waste by informal reprocessing of printed circuit boards, batteries and cables. The complete step of the process is accomplished by people involved irrespective of gender and age who work without using proper protection in a harmful environment. In a study by Ha et al. (2009) observed high doses of heavy metal in soil at a recycling slum in Bangalore that contained up to 4.6 mg kg^{-1} In, 180 mg kg^{-1} Sb, 2850 mg kg^{-1} Pb, 39 mg kg^{-1} Cd, 49 mg kg^{-1} Hg, 957 mg kg^{-1} Sn and 2.7 mg kg^{-1} Bi. The concentrations recorded were 100 times more than control site. A similar study by Pradhan and Kumar (2014) analysed heavy metals in soil, water and plant samples collected from recycling sites in Mandoli Industrial Area, Delhi. Results revealed that a high level of heavy metals concentration was found in soil samples like Cu (115.50 mg kg^{-1}), As (17.08 mg kg^{-1}), Pb (2645.31 mg kg^{-1}), Cd (1.29 mg kg^{-1}), Se (12.67 mg kg^{-1}), Zn (776.84 mg kg^{-1}), native plant samples (*Cynodon dactylon*) and water samples.

12.3.2 Hazardous Chemical Toxicity

E-waste is different from other forms of wastes which comprise composite mixtures of probable environmental contaminants. E-waste also contains some uncommon potential contaminants even in other polluted sites. In the manufacturing of electrical items, some heavy metals contaminants are used, while during combustion of E-waste at low temperature, other contaminants such as polycyclic aromatic hydrocarbons are produced. Important metals (Cu, platinum group) along with potential environmental contaminants, especially Ni, Sb, Hg, Pb, Cd, polybrominated diphenyl ethers and polychlorinated biphenyls, are generally present in the E-waste. Dioxins, furans, polycyclic aromatic hydrocarbons, polybrominated diphenyl ethers, polychlorinated biphenyls and polychlorinated dibenzo-p-dioxins and dibenzofurans and hydrogen chloride could be generated due to the burning of E-waste that are highly contaminated pollutants (Darnerud et al. 2001; Martin et al. 2003).

Open burning and labour-intensive treatment are widely used basic methods in the recycling of E-waste. In comparison with domestic waste, ignition of insulated wire produced 100X more dioxins (Gullett et al. 2007). Flame retardants such as polybrominated diphenyl ethers are synthesized into plastics and other components. Polybrominated diphenyl ethers and plastics can leach out from the surface of E-waste into the atmosphere due to the absence of chemical bonds between them (Deng et al. 2007). Lipophilic character of polybrominated diphenyl ethers causes bioaccumulation in the organisms and biomagnification in the food chains (Deng et al. 2007). Endocrine disrupting properties are also found in polybrominated diphenyl ethers (Tseng et al. 2008). During the recycling procedures, ignition products of polyvinyl chloride in electrical wires can emit or form a number of highly lethal pollutants like polychlorinated biphenyls in capacitors/transformers, polybrominated diphenyl ethers which are used as brominated flame retardants in the circuit board and polychlorinated dibenzo-p-dioxins and dibenzofurans (Wang et al. 2005). Soil samples were gathered by Leung et al. (2007) from the site where it was usual to liquify circuit boards, incinerate things as cable covering to recover copper wire and employ open-pit acid leaching for extraction of valuable metals. Their research works concentrated on polybrominated diphenyl ethers and polychlorinated dibenzo-p-dioxins along with dibenzofurans, that is, polybrominated diphenyl ethers and polychlorinated dibenzo-p-dioxins and dibenzofurans. Carcinogens in duck ponds and paddies were 263–604 ng g^{-1}, dry weight and 34.7–70.9 ng g^{-1} which exceeded from control sites.

A similar study by Luo et al. (2007b) accounted that carps collected from the Nanyang River, near Guiyu, bioaccumulated polybrominated diphenyl ethers to high level, i.e. 766 ng g^{-1} (fresh weight). Expectedly, Luo et al. (2007a) in the further study accounted for high polybrominated diphenyl ether levels in the sediments, i.e. up to 16,000 ng g^{-1} of the Nanyang River. A similar study was done by Wu et al. (2008) and found that water snake near (the top predator) an E-waste recycling yard had around 1091 ng g^{-1} polybrominated diphenyl ethers and

16,512 ng g^{-1} polychlorinated biphenyls on a wet weight basis. Other than polybrominated diphenyl ethers, brominated flame retardants like decabromodiphenyl ethane, tetra-bromobisphenol A bis (2, 3-dibromopropyl) ether and 1, 2-bis (2, 4, 6-tribromophenoxy) ethane are commonly found in the different ecosystem of Pearl River Delta (Shi et al. 2009). All these have caused a high level of toxic pollutants in the ambient atmosphere that further degrade the ecosystem and human well-being (Wong et al. 2007; Yu et al. 2006; Deng et al. 2006).

12.4 Effect on Human Health

Hazardous waste may adversely affect the health of the local inhabitants and workers that may involve any organ failure depending on the contact of any specific type of chemical(s), exposure time, exposed individual's characteristics like age and sex, body weight, immunological status, etc. Exposure routes may differ depending on the kind of substance involved and their recycling process. The general route followed by the harmful components emerging from E-waste is either via inhalation, ingestion or dermal contact. In addition to this, people can come in contact with associated pollutants through contaminated air, soil, water or food. Also, additional exposure risks are faced by pregnant women, foetuses, children, elderly population, disabled persons, workers and local residents (Grant et al. 2013). Among them, children are at a higher risk due to other routes of exposure like placental exposure or breastfeeding, their altering physiology like high consumption of water and food and low toxin elimination rate and high risk-taking behaviours like hand to mouth activity in recent years (Pronczuk de Garbino 2004). Besides, the children of E-waste manufacturing and recycling workers get contaminated by their parents' skin or clothes and direct exposure if the recycling process is happening in nearby places or homes.

Heavy metals penetrate the human body via oral intake, dermal contact and inhalation. Water and food intake are the major sources of oral exposure to heavy metals (Zheng et al. 2013; Xu et al. 2006). Food crops bioaccumulate heavy metals via wastewater irrigation (Singh et al. 2010), atmospheric deposition (Bi et al. 2009) or contaminated soil (Zhuang et al. 2009). Contaminated soil and feeds result in an elevated level of heavy metals in meat products (Cang et al. 2004; Gonzalez-Weller et al. 2006). A number of studies revealed that Pb, Cd, Zn and Cu are potential human carcinogens that are related to several disorders like the nervous system, blood, urine, cardiovascular and bone diseases (Jarup 2003; Brewer 2010; Muyssen et al. 2006). A similar study by Thomas et al. (2009) speculated that Cd and other heavy metals cause early kidney damage. Several studies have also found that Cu leads to liver damage, Pb results in behaviour and learning disabilities and Cd increases the risk of kidney damage (Bhutta et al. 2011; Chan et al. 2013; Yan et al. 2013). These studies emphasize the significance of assessment of heavy metal risk and exposure to the local inhabitants and labours in E-waste recycling areas.

Table 12.2 Health effects and exposure route of different pollutant emitted from E-waste

S. no.	Pollutant	Exposure route	Effects
1.	Heavy metals	Air, dust, water, soil, food	Human carcinogen; affect neurodevelopmental activity, cognition, learning and behaviour; and affect neuromotor skills
2.	PBDEs	Air, dust, food	Thyroid hormone disruption, hyperactivity, cognitive deficits and impaired memory
3.	PCBs	Air, dust, seafood	Affect neuropsychological functions in children, including general cognition, visual-spatial function, memory, attention, executive functions and motor function
4.	PCDD/PCDFs	Air, dust, soil, food	Reproductive and neurobehavioural development, immune development, carcinogenicity
5.	PAHs	Air, dust, soil, food	Carcinogen and mutagen affect child neurodevelopment and lead to IQ deficits

A comparable study by Ha et al. (2009) in recycling sites such as Guiyu in China and Bangalore in India speculated that heavy metals and their associated pollutants cause severe damage to the environment and human health. This is due to a high penetration rate of heavy metals in soil and then to plants where it bio-accumulates and further transported to trophic level. They found an elevated level of heavy metals like Pb, Bi, Cu, Zn, Bi, In and Sn in the soil near recycling workshops. Hair samples of workers have increased the level of Cd, Ag, Cu, Sb and Bi. As compared to control, ten times higher level of polybrominated diphenyl ethers was found in the serum of workers at recycling workshops (Sjödin et al. 1999). Also, the children and neonates have elevated levels of Cr, Ni, Cd and polybrominated diphenyl ethers than controls (Guo et al. 2010; Wu et al. 2010). A parallel study by Asante et al. (2012) at Agbogbloshie, Accra and Ghana found relatively high traces of heavy metals in the urine of workers. These studies indicated that E-waste disposal has a serious negative impact on human health and the environment (Table 12.2).

12.5 Conclusion

Already a global concern regarding E-waste management has resulted in many policies and legislation. The European Union has implemented two such legislations to address the concern over the management of E-waste. The first directive is on E-waste management, i.e. waste electrical and electronic equipment, which directs the manufacturer about their responsibility for management of E-waste; this strategy is called greener electronics (Chen et al. 2011; Pant et al. 2012). Similarly, 'Restriction on the use of Hazardous Substances (RoHS) Directive' limits the application of heavy metals like Cd, Pb, Hg, Cr (VI), polybrominated diphenyl ethers and polybrominated biphenyls in the manufacture of new devices (Chen et al. 2011).

Likewise, India drafted 'Hazardous Materials Laws and Rules' in 2007 for addressing the same issue (LaDou and Lovegrove 2008).

Non-governmental organizations have played a crucial role by placing pressure on manufacturers to eliminate or limit the use of environmental contaminants during manufacturing of their products. One such concept is extended producer responsibility (EPR) that provides incentives for redesigning and removing toxic contaminants from their products (Betts 2008). Many manufacturers of electronic goods have started exploring innovative measures to improve recycling and safe disposal of E-waste. Developed countries have the self-interest to mitigate the harmful environmental effects of E-waste as it will negatively affect the food quality and quantity and other goods that are manufactured and imported from developing countries. However, there is limited information on environmental effects, risks on human health and remediation techniques for most of the E-waste contaminants; therefore, it is anticipated that more safe and scientific recycling options of E-waste will be adopted to avoid damage of the local environment and human health.

Acknowledgement The authors are thankful to the Dean & Head, Department of Environment and Sustainable Development and Director, Institute of Environment and Sustainable Development, Banaras Hindu University, for providing necessary facilities. RPS is thankful to the Department of Science and Technology for providing financial support (DST-SERB P07-678). BS is thankful to the University Grants Commission for awarding Junior and Senior Research Fellowship. BV is also thankful to the Council of Scientific and Industrial Research for awarding Senior Research Fellowship.

Conflict of Interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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