University of Tehran Press

Pollution

Print ISSN: 2383-451X
Online ISSN: 2383-4501

https://jpoll.ut.ac.ir/

Status, Health Effects and Remediation Techniques of E-waste – A Review

Shailu Dalal Guin | Surinder Deswal✉

Civil Engineering Department, National Institute of Technology Kurukshetra, Kurukshetra-136119, Haryana, India.

Article Info

Article type:
Review Paper

Article history:
Received: 30 Apr 2023
Revised: 12 Jun 2023
Accepted: 07 Jul 2023

Keywords:
E-waste,
Biological remediation techniques
Environmentally sustainable management
Extended Producer Responsibility

ABSTRACT

The annual global generation of e-waste is estimated to be 59.08 million tonnes (7.37 kg per capita), out of which the major chunk is being processed in informal sector using primitive and hazardous methods in developing countries due to cheap labour, less stringent laws and regulatory policies. Despite the fact the annual global value of e-waste industry being about USD 62.5 billion that provides employment to millions in developing countries, the unstructured/informal operations in e-waste sector had and have been causing hazardous health issues in human and environment along with unlawful activities. Many studies have been reported on wide array of interrelated aspects and issues of e-waste, but only few studies have reviewed potential remediation techniques that can take care of the increasing e-waste and its sustainable management. Therefore, disposal and remediation techniques for polluted sites have been the key concerns in the field of environmentally sustainable management (ESM) of e-waste. The present review revealed that of all the classic and hybrid remediation techniques, the biological remediation techniques being eco-friendly and cost effective needs to be explored for metal removing from contaminated environment. The review also concludes the imminent necessity of ESM by framing and implementing regulations and laws essentially incorporating Extended Producer Responsibility (EPR) in developing countries. The review of Indian scenario suggests the scope of startups for the sustainable recycling of e-waste to achieve healthy environment, employment and economic opportunities.

Cite this article: Dalal Guin, Sh., & Deswal, S. (2023). Status, Health Effects and Remediation Techniques of E-waste – A Review. *Pollution*, 9 (4), 1676-1705.
https://doi.org/10.22059/POLL.2023.358554.1897

DOI: https://doi.org/10.22059/POLL.2023.358554.1897

INTRODUCTION

Electrical and Electronic Equipment (EEE) are one of the major necessities of modern technology savvy lifestyle. EEE involves items with circuit or electrical components that works with the help of power supply. Majority of household or commercial use product having electrical circuits and component fall into this category. EEE becomes when discarded with intention of not using them (European Parliament, 2003; MoEFCC, 2003; Li et al., 2010; European Parliament, 2012; Grant et al., 2013; Garlapati, 2016; MoEFCC, 2022). Once discarded, each Waste Electrical and Electronic Equipment (WEEE) has to be treated differently in order to protect the environment and human health from them. EEE was initially a luxury, then it became a necessity, and now a major environmental issue with potential health hazards (Robinson, 2009; Sansotera et al., 2013; Cesaro et al., 2017; Islam et al., 2020; Abalansa et al., 2021). Major reason of EEE waste becoming environmental and health hazards include overproduction, delay in recycling after being discarded, and unstructured/informal recycling

*Corresponding Author Email: *sdeswal@nitkkr.ac.in*

and treatment (Streicher-Porte, 2005; Wang et al., 2008; Manhart et al., 2011; Liu et al., 2014; Cesaro et al., 2017; Ignatuschtschenko, 2017; Isimekhai, 2017; Tsydenova & Heyken, 2018). The delay in recycling may be due to many reasons, including inaccessibility in collection of these products (Forti *et al.*, 2020).

The EEE systems become obsolete very soon due to fast technological changes resulting in an increase in the e-waste load of the nation (Kasper et al 2015). Presently. the annual global generation of e-waste is estimated to be 59.08 million tonnes that amounting to 7.37 kg per capita (Forti et al., 2020; Abalansa et al., 2021). China, United States of America, Australia, and India are among the leading producers of e-waste in the world. India is the fourth largest producer of e-waste globally (ASSOCHAM, 2016). Being one of the world's largest EEE manufacturing industry, India has not only had its indigenous pile of e-waste to take care but it has also become the dumping ground for developed countries (Gill, 2019). In fact, the developing countries suffer more from the impact of hazardous e-waste because used EEE are donated, exported or dumped these countries by the developed countries on various pretext, resulting in huge piles of e-waste. In countries like China, Brazil, Mexico, Ghana and Nigeria where e-waste is being dismantled/ recycled largely in unstructured sector under hazardous environment causing human health and adverse impact on environment (Chen et al., 2011; Cesaro et al., 2017; Daum et al., 2017; Fu et al., 2018; Bogdan-Marrtin, 2022). Studies suggest a strong linkage of human and environmental health to toxins released from e-waste exposure (Chandna & Deswal, 2005; Zhao et al., 2009; Tsydenova & Bengtsson, 2011; Heacock et al., 2016; Cesaro et al., 2017). The wide range of health effects include – behavioral changes in children and in pregnant women; stunted growth and development of children; lower birthweight, length, head circumference, and Apgar scores; induced lung function; inconsistent functioning of thyroid gland; neurodevelopment variance; and many more (Grant et al., 2013; Yang et al., 2013; Ben et al., 2014; Eguchi et al., 2015; Xu et al., 2016; Li et al., 2018; Zeng et al., 2018; Zeng et al., 2019). In fact, observed notable changes in cellular level requires an urgent attention for more research, with focus on birthing mothers and kids, and environmentally sustainable management (ESM) of e-waste (Brune et al., 2013).

For ESM of e-waste, it needs to be recycled so as to avoid the increasing landfills and its adverse impact on health and environment. Though, countries across the world have formally developed and implemented bylaws to recycle e-waste (Bogdan-Martin, 2022; Wagner et al., 2022); but due to lack in enforcement and other reasons, a huge chunk of e-waste is still being treated in unorganized/informal ways leading to pollution and bioleaching of hazardous chemicals in the environment. This status quo points towards the need for environmentally sustainable management (ESM) of e-waste by utilizing environmental friendly and efficient remediation techniques, particularly biological methods as these methods have been valued over other methods due to low investment, less labour and power input, and efficient in diverse and adverse conditions (Agate, 1996; Pathak et al., 2014; Yang et al., 2017; Benassi et al., 2019; Yesil & Tugtas, 2019; Yang et al., 2020).

Though many review studies have been reported on e-waste at various interval of time in the past; however, the focused aspects of e-waste have been varying in the reported studies due to wide array of interrelated aspects and issues. Despite many review studies on various aspects and issues of e-waste, the review of remediation techniques having potential to take care of the increasing e-waste and its sustainable management has been lacking. Further, the policies and regulations regarding e-waste handling and management in developing countries who have been at the receiving end of the deleterious impacts of e-waste dumping. In view of this, the present paper aims to review the status, issues and health effects e-waste with focus on potential remediation techniques and sustainable management of e-waste, along with the policies and regulations regarding e-waste handling and management in India. It may not be possible to include all the research studies of e-waste covering wide range of related aspects and issues; therefore, this paper seeks to highlight the significant contributions to the emerging environmental issue of e-waste resulting from technological advancements with a focus on remediation techniques – classic (physical, chemical and biological) and hybrid (physico-chemical, physio-biological and chemical-biological) techniques, including ESM of e-waste.

E-WASTE

Electronic waste, commonly referred as e-waste, embraces diverse forms of electrical and electronic equipment (EEE) those are of no value and discarded off without any intention to reuse them (Li et al., 2010; European Parliament, 2012; Grant et al., 2013; Garlapati, 2016; MoEFCC, 2022).

Classification of E-waste

E-waste composition differs depending upon the material EEE products are made of, and contains diverse substances that need to be characterized and classified under safe and unsafe categories based on their usage and nature. European Commission (EC) and Ministry of Environment, Forest and Climate Change (MoEFCC), Government of India has suggested different categories for e-waste through its directives with comprehensive choice based on European Waste Electrical and Electronic Equipment (WEEE) as presented in Fig.1 (European Parliament, 2003 & 2012; Garlapati, 2016, MoEFCC, 2022). The categorization/characterization include household, IT and telecommunication, electrical and electronic gadgets, illumination devices, toys leisure and sports gadgets, medical appliances, monitoring and controlling equipment and automatic dispensers.

In order to elucidate whether the EEE can be reused or thrown away, EEE was further classified based on their usage and when they can be termed as WEEE or e-waste (Cuchiella et al., 2015), as presented in Table 1.

Further, Garlapati (2016) has proposed the classification of e-waste focusing on the hazardous gadgets and/or components, along with the associated toxin (Table 2).

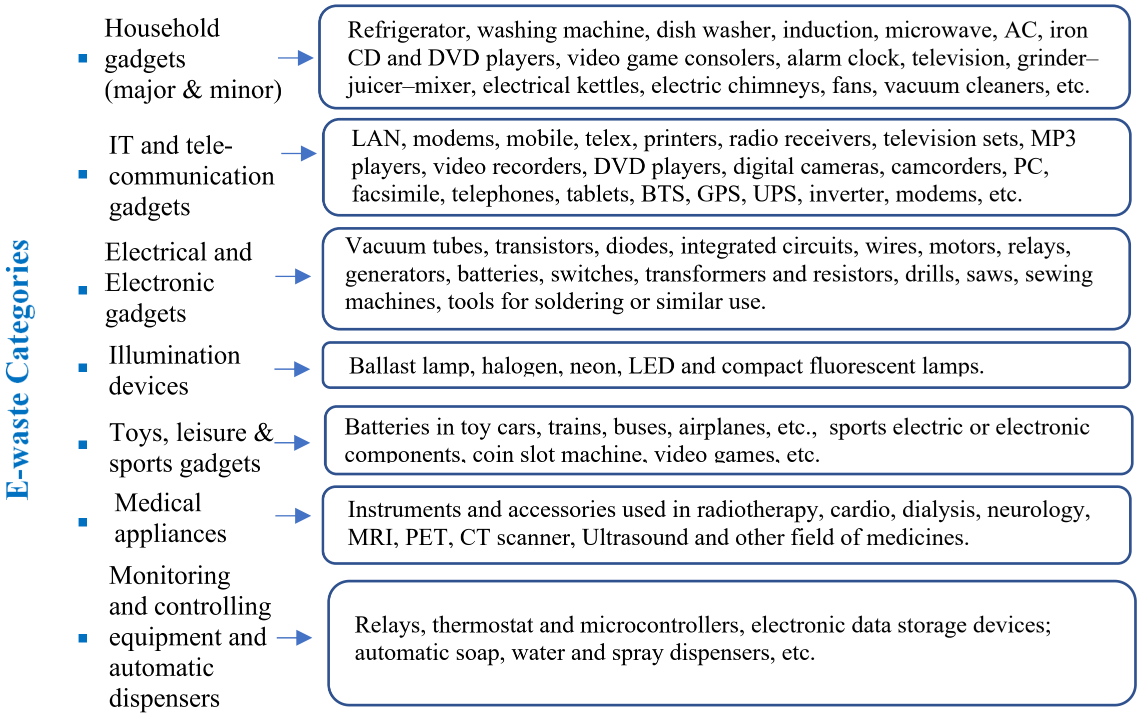

Fig. 1. E-waste Categorization on the Basis of European Commission Directives

Table 1. Classification of E-waste on the Basis of Usage *(Source: Cuchiella et al., 2015)*

Status of EEE	Description	Waste or Non-waste
New and Functional EEE	New products or components being delivered and shipped between different countries.	**Non-waste** by default (new products for distribution).
Used and functioning EEE suitable for direct use	Equipment need no further repair, or hardware upgradation.	**Non-waste**; however, in some countries there are certain restrictions in export and import.
Used and non-functioning but repairable EEE	Equipment that can be repaired returning it to a working condition performing the essential functions it was designed for. Testing is required to determine this condition.	Under discussion by Basel Parties as many countries remove the hazardous parts and consider it as **waste**, while others classify it as **non-waste**.
Used and non-functioning and non-repairable EEE	Common form of e-waste can be mislabelled as used EEE.	Should be classified as **waste**.
WEEE	EEE waste within the meaning of waste framework directive context including components and sub-assemblies.	Should be classified as **waste**.

Table 2. Classification of E-waste on the Basis of Type of Toxins and Hazardous Components *(Source: Garlapati, 2016)*

Type of Toxin	Element / Compound	Hazardous Gadget and/or Component
Heavy metals and other material	Arsenic (As)	Light emitting diode
	Barium (Ba)	Getters in cathode ray tube (CRT)
	Beryllium (Br)	Rectifiers and x-ray lenses
	Cadmium	CRT, batteries, printer inks and toners
	Chromium VI	Data tapes, floppy-disks
	Lead (Pb)	Batteries, CRT, printed wiring boards
	Lithium (Li)	Batteries
	Mercury (Hg)	Fluorescent lamps, batteries, switches
	Nickle (Ni)	Batteries, CRT
	Rare earth elements: Yttrium (Y), Europium (Eu)	CRT
	Selenium (Se)	Photo drums of photocopying machines
	Zinc sulphide	CRT
Radioactive substances	Americium (Am)	Medical gadgets, fire and smoke detectors
Polyhalogenated compounds	Polychlorinated biphenyls (PCB)	Condensers, transformers
	Polybrominated biphenyls (PBB)	Fire retardants
	Polybrominated diphenyl ethers (PBDE)	Plastics
	Chlorofluorocarbon (CFC)	Cooling unit, insulation foam
	Polyvinyl chloride (PVC)	Cable insulation
Other	Toner dust	Cartridges of printers and photocopiers

All the above three classifications represent different context but in the same perspective of e-waste, and are useful in sorting gadgets and/or their components into groups or categories having similarities and help the researchers and others to communicate and present clearly the type of e-waste in question.

Valuables from E-waste

Discarded e-waste is a costly resource having metallic content of about 60%, which includes precious metals such as copper, gold, silver, platinum, neodymium, indium, gallium, and rare metals like yttrium (Vats & Singh, 2015; Pourhowannarat et al., 2016; Pourhossein & Mousavi 2018; Awasthi et al., 2019; Islam et al., 2020). For instance, a high-end mobile can provide 19% copper and approximately 5 to 8 % of iron and even precious metals like gold and silver; and many of the heavy metal, such as copper, iron, gold, nickel and silicon, can be easily extracted from e-waste (Zhou et al., 2020). The resource content of valuable metals are 40-50 times richer than natural deposits in some of the discarded e-waste (Collins et al., 2012). Europium and terbium, two in-demand and precious rare earth minerals, are also part of e-waste (Magalini et al., 2015).

As the natural supply of precious and rare earth elements has been steadily declining, so less costly and plentiful raw materials available in e-waste has become a major source of these elements. This increasing value of the e-waste industry is one of the main drivers of the e-waste problem. Wang et al. (2008) reported that the increasing demand for cheaper and low-cost raw materials accounts for the surge in illegal import of e-waste into China.

STATUS OF E-WASTE AND ISSUES THEREOF

The pollution stress due to the ever increasing e-waste has been immense. The annual global e-waste generation was 37.64 million tons (Mt) in 2015 that increased exponentially to about 59.08 Mt in 2019 accounting for 7.37 kg per capita, and is estimated to increase to 82.34 Mt by 2030 (Leur & Walter, 2019; Forti et al., 2020; Abalansa et al., 2021). Among various continents, Asia contributes maximum amount of e-waste (18.2 Mt, i.e. 41% of global e-waste) in 2016 followed by Europe (12 Mt) and N & S America (3 Mt). In Asia, China produces maximum e-waste followed by India which is the second largest generator of e-waste and ranks as 4th highest globally. According to ASSOCHAM (2016), India is estimated to produce 5.7 Mt of e-waste in 2020. The overall impact of e-waste on the environment by the African nations is estimated to be 5 % of international e-waste burden. The African countries of Ghana and Nigeria are major consumers of e-waste largely being exported from USA and Europe (Sullivan, 2014). The unstructured e-waste processing plants in Ghana were responsible for creating immense stress of about 2.8 Mt way back in the year 2009 (Pwamang, 2013); and Nigeria about 2.77 Mt of e-waste in 2016 (Leur & Walter, 2019). In American continents, Brazil is estimated to have produced 1.65 million tons of e-waste stress in 2016 and Mexico about 1.1 Mt during 2015 that increased to 3.9 Mt in 2018 (Sotelo et al., 2016; ILO, 2019).

Studies have highlighted that very few developed countries (Taiwan, South Korea, Japan, Australia, and few other) dispose the e-waste in safe and environmental-friendly manner. Others, either due to lack of viable technological skills or higher costs or both, donate/export/dump e-waste in developing Asian, African and Latin American countries. While the African countries re-claim and again puts the electronic item into use, but the Asian and Latin American countries dismantle them using cheap labour with no means of protection from hazardous waste thus becoming a cause of health hazard (Wong et al., 2007). On the other hand, the developed countries have their own diverse e-waste regulatory agendas and laws (Zhang et al., 2019). Therefore, it needs to be looked at whether there are significant disparities in e-waste creation among developing and developed economies as well as between nations with and without e-waste regulatory regimes, and the export/dumping of e-waste by developed nations to developing nations.

It has been observed that higher internet penetration in developing countries leads to higher e-waste; while higher literacy rates in developed countries lead to less e-waste. But when it comes to e-waste policy, a higher urban population without a regulatory legal framework reportedly leads to higher e-waste. Similarly, if there is a legal framework imposed with higher internet penetration, less generation of e-waste should follow. However, the ability to sustain an e-waste management is greater in advanced countries (Li et al., 2010). Mejame et al. (2020) reported that the developing nations contribute more to e-waste because they lack clearly defined e-waste policies. But the e-waste management system and policies have been emphasized differently in developed and developing countries (Liddle, 2013; Kaminsky, 2016). There are some developing countries having e-waste policies; whereas, many developed ones do not have regulatory policies in place (Liddle, 2013; Pariatamby & Victor, 2013; Kaminsky, 2016). Thus, it can be safely inferenced that the development of any nation is not determined by its e-waste regulations. In an experimental study, Kalia et al., (2022) concluded that e-waste generation decreases with more education in the developed countries; on the contrary, in the developing nations the internet penetration has been leading to more production of e-waste. Kalia et al. (2022) has also reported that a rise in education rates in industrialized nations leads to decline in e-waste. Islam & Huda (2019) observed that the expanding middle and lower classes in developing nations with increasing spending power may have an impact on rising electronic gadget adoption, and in turn generation of e-waste. This is possibly due to the fact that developed countries have already reached the capacity regarding internet penetration, whilst developing countries have still not reached this capacity. Further, due to increased information and literacy, there seems to be a transition in industrialized countries from capitalism to ecology, or at least understanding or awareness about the side effects of e-waste. Additionally, it suggests that the long-term focus should be on human resources rather than the arbitrary comfort that electronic equipment provide.

However, one of the major reason of reduced e-waste in the developed nations has been due to continuous dumping/exporting most of their e-waste to the developing nations. Such inappropriate practices are burdening the unrestrained landfills of many Asian and African countries which is unethical and unjustifiable in longer terms (Vidali, 2001). Amongst the most polluted e-waste sites of the world are Agbogbloshie in Ghana (Africa) and Guiyu city in China (Asia). Guiyu is referred as the e-graveyard of Earth due to its dubious ways of e-waste recycling (Daum et al., 2017).

For a section of society in the developing countries, the e-waste sector is a significant source of money and employment. About 18 million people were employed globally in the e-waste sector in 2010 (Leur & Walter, 2019), with the industry's annual global value estimated to be USD 62.5 billion (Balde et al., 2017). In Ghana, the industry supports between 20,300 and 2,00,000 workers in the unorganized sector, with an estimated annual worth of USD 105-268 million (Daum et al., 2017). The e-waste sector in Nigeria provides a source of income for more than 1,30,000 unofficial e-waste labourers that includes the collectors and re-sellers (Leur & Walter, 2019). In Brazil, e-waste industry provides an income source to about 4,00,000 to 10,00,000 people (Migliano, 2014). According to Press Trust of India (PTI), the e-waste business in India generates 4,50,000 direct and 1,80,000 indirect jobs annually, with an estimated value of roughly USD 3 billion (Kopacek, 2021). It employs more than 30,000 informal workers in Seelampur and over 25,000 in Delhi alone. According to Cordova-Pizarro et al. (2019), the PCBs of mobile phones in e-waste in Mexico are worth USD 11.3 to USD 12.4 million annually. In China, the e-waste business is expected to employ 7 lakh people (Wei & Liu, 2012); and by 2030, that number is expected to reach 23.8 million (Greenpeace, 2019).

Fate of E-waste

The dilemma with e-waste is that it may be generated in one country but its final destination may be anywhere else in the globe. It is estimated that approximately 23 % of e-waste produced in developed countries is being sent to developing nation (UNEP, 2012). Many developing countries import e-waste in huge quantities; as recycling of this e-waste has become an important part of their '*formal*' or '*informal*' economy as it has paved a new form of business and employment (mostly illegal).

Recycling of E-waste formally includes differently constructed facilities with proper equipment and technology capable of safe extraction of the material and ensuring safe working environment. However, formal recycling plants are difficult to build and run in developing nations due to high expenses. Therefore, *informal* e-waste recycling has become like a business which is typically characterized as unauthentic, illegal, without any basic structure and ungoverned (Chen et al., 2011). Due to sub-standard safety measures in such *informal* recycling facilities, the employees are exposed to serious health hazards. Further, even in case of modern technical recycling facilities, people in the surroundings may be at the risk of exposure (Freeman 1989, Gaidajis et al., 2010, Cucchiella et al., 2015).

Although, many countries have permitted and approved formal e-waste initiatives that has allowed authorized acquisition of e-waste from private businesses or government organizations, but it requires monitored disassembly and recovery facilities that take into account human and environmental demands and necessitate the employment of high-tech equipment and techniques (Ceballos & Dong, 2016). However, in actual practice, there have been less formal recycling operations in the e-waste market as a result of which official e-waste activities become costly and capital intensive (Perkins et al., 2014).

Recent studies have reported that less than 20% of global e-waste production is recycled in the formal sector (Forti et al., 2020). Taiwan, South Korea and Japan formally recycle about 75-82 % of their e-waste; and some other developed economies, such as Canada, Australia and European countries have been focusing in developing their own formal recycling industry and/or establishing tie ups with other countries having strong rules of e-waste recycling. However, authorized formal recovery and recycling systems in developing countries are few and in early stages of development. There are only 109 authorized recovery and recycling systems accounting for 2% of all practices in China (Fu et al., 2018), 150-312 in India (Leur & Walter, 2019; Turaga, 2019), 4 in Nigeria (Nnorom, 2020), 4 in Mexico (Denogean, 2016) and 1 in Ghana (Daum et al., 2017).

Unlawful Activities

Since informal operations are more profitable than legal ones, so there has been a far bigger unstructured e-waste sector in developing nations like China, India, Ghana, Nigeria, Mexico and Brazil. The unstructured e-waste sector has also encouraged other unlawful activities, such as informal labourers, migration of people from nearby towns/countries, child labour, etc. Informal operations in China accounts for around 98 % of all e-waste activities (Ignatuschtschenko, 2017). In India, 95 % of e-waste sector activities are informal, making them almost as significant as those in China (Hinchliffe & Gunsilius, 2017). In Africa (Ghana and Nigeria) and America (Mexico and Brazil) too, a bigger portion of e-waste industry is defined by un-authorized operations. The majority of the informal laborers, about 70% in Guiyu (China) and about 80% in Agbogbloshie (Ghana), are migrants from surrounding towns and/or nearby adjoining nations (Wei, 2012; Amankwaa, 2013); resulting in relocation as e-waste labourers (Wang, 2016; Sovacool, 2019). Similar findings have been reported from Nigeria (Manhart et al., 2011), Mexico (Tsydenova & Heyken, 2018) where migrant workers participate in e-waste activities so as to have an extra revenue source. In India, e-waste workers basically migrate from Indian states of Bihar, UP, West Bengal and many other backward areas/regions, and from the neighboring parts of Bangladesh (Streicher-Porte et al., 2005).

In the e-waste industry, child labour has been prevalent particularly on the weekends and during school breaks (Isimekhai, 2017), when youngsters join forces with families living in the near vicinity of e-waste landfill sites (The Economist, 2021; Sieff, 2021). Children are often engaged in the process of separation of components of e-waste (Ladou & Lovegrove, 2008). Studies of African countries of Ghana and Nigeria also suggest the involvement of child labour in e-waste operations (Amankwaa, 2013; Obaje, 2013). In China, children have been frequently given the responsibility of disassembling or burning e-waste in order to recover valuable materials (Puckett et al., 2002). Between 35,000 and 500,000 children under the age of 16 are working as labour in various stages of e-waste activities in India (ASSOCHAM, 2016; Joon et al., 2017). Involvement of child labour, aged between 8 and 15 years, has also been reported in Mexican e-waste industry (Cordova-Pizarro et al., 2019). The engagement of children in such hazardous environment has potential unidentified health effects (Obaje, 2013).

EFFECTS OF EXPOSURE ON HUMAN HEALTH

No restrictions in the safety rules, safety equipment, legislation policies and implementation of safe disposal of e-waste and other electronic goods have caused hazardous health issues in human and environment. The impact of e-waste on human health is a notable issue in certain developing nations like India and China (Wang & Guo, 2006; Chan et al., 2007; Qu et al., 2007; Zhao et al., 2008; Xing et al., 2009; Wang et al., 2009; Guo et al., 2010; Fu et al., 2018). Improper handling of WEEE generates heavy metals that are hazardous to human health and the environment (Cesaro et al., 2017). This has become a matter of concern for developing countries not only because of the huge amount of e-waste being imported, but also due to the range of toxic waste it generates.

A major risk on health issues comes from heavy metals and halogenated compounds released from e-waste. Studies have reported that the toxic metallic content and polyhalogenated organics, which also includes PCBs and PBDEs, is released from e-waste resulting in harmful health effects on humans and also on environment (Robinson, 2009). Old electronic products, such as refrigerators and air conditioners, contain chloro-fluoro carbons (CFC) that have the potential to deplete stratospheric ozone. When such electronic wastes are kept in the landfill, CFCs are slowly released in the nature (Scheutz et al., 2004). Metals including Pd, Cd, Hg, and Ni as well as organic substances like flame retardants, CFCs, and PAHs are all found in e-waste (Guo et al., 2010). E-waste recycling also recovers precious materials such as Fe, Al, Cu, Ag, and rare earth metals, though their prolonged exposure can be harmful (Tsydenova & Bengtsson, 2011; Matsukami et al., 2015). Several studies have reported substantially higher levels of PBDEs and PAHs as well as the heavy metals lead and cadmium in exposed populations than non-exposed individuals (Zhao et al. 2009; Chan et al. 2013a; Yang et al., 2013; Xu et al., 2015a; Xu et al., 2016; Li et al., 2018; Zhang et al., 2018; Huo et al., 2019b; Zeng et al., 2019b).

Both human and environmental health are at risk from these environmental toxins (Heacock et al., 2016). Chen et al. (2009) observed a major difference in a group of workers having raised levels of serum PBDEs and thyroid-stimulating hormone (TSH) versus the control group of co-workers of an e-waste company in China. In two trials, PBDE concentrations in the umbilical cord and placenta were found to be inversely linked with infant head size, BMI and Apgar1 scores (Xu et al., 2015b; Li et al., 2018); whereas, blood PAHs were found to be inversely linked with height and chest circumference in children aged 3–7 years (Xu et al., 2015c).

Lead has also been reported to be a well-known neurotoxin, causing cognitive impairment and organ system weakness in the neurological, circulatory and reproductive system. According to Needleman (2009), there is no safe level of lead exposure for children's neurological systems. Lead exposure has also been linked to stunted growth and development (Yang et al., 2013; Xu et al., 2015c; Xu et al., 2016; Zeng et al., 2019b). In an e-waste recycling zone, Cao et al. (2018) observed that lead exposure contributed to the elevated percentage of peripheral CD^{4+} central memory T cells. Cadmium is also highly poisonous, especially to kidneys and bones due to its property of bioaccumulation. Xu et al. (2016) has reported a 10 ng/g rise in endometrial cadmium level associated to a weight loss of 205 grams and a body length reduction of 0.44

centimeter. Urinary cadmium from the mother has been linked to lower birthweight, length, head circumference, and Apgar scores (a scoring system that provide a standardized assessment for infants after delivery) in new born female babies (Zheng et al., 2017 b; Zeng et al., 2018). Report of behavioural problems in children with greater amounts of Pb, Cd, and Mn in blood is also reported (Liu et al., 2014). In fact, children with high blood lead (Pb >10 g/dL) is found to have a 24-fold increased risk of attention deficit hyperactivity disorder compared to children with no lead poisoning**.** Thyroid gland's activity is found to be affected by e-waste-induced hazardous compounds (Xu et al., 2014b; Xu et al., 2015b; Zeng et al. 2019b). Studies suggest the effect of lead exposure on the transcription of RBC integrins (CD44 and CD58) in infants and toddlers that has resulted in decreased erythrocyte immunity due to long-term environmental lead contamination (Ben et al., 2014; Xu et al., 2014a; Yang et al., 2014; Eguchi et al., 2015; Zheng et al., 2017a; Guo et al., 2019; Huo et al., 2019a). Some category of e-waste produces chemical which bring about carcinogenic changes and may disrupt the endocrine glands resulting in lifelong abnormal changes. 8-hydroxydeoxyguanosine, a urinary biomarker of generalized cellular oxidative stress, had raised level in the urine of workers of e-waste post work shift (Wang et al., 2010). Grant et al. (2013) described lowered lung function in boys of age between 8 to 9 years of an e-waste recycling town in comparison to a group of control population of boys of the same age group where this effect was not observed as the town had no exposure of e-waste. In the same set of children, an important negative correlation was observed amid forced vital capacity, a measure of lung function, and blood chromium concentrations have also been reported.

Though it is difficult to enumerate the number of harmful substances in e-waste that humans could be exposed directly or indirectly; however, more hostile health effects are anticipated due to exposure to e-waste that are still to be noted. Even if daily exposure is low, cumulative exposure is often high and extremely hard to measure (Chan et al., 2013b). Thus, a mixture of e-waste can be hazardous and may go undocumented for its difficulties in the study, on the contrary the effect of a one chemical at certain level are relatively easy to study in an elaborate manner.

REMEDIATION TECHNIQUES

Remediation is the process of removing contaminants from sites that have been polluted from industrial, manufacturing, mining, and commercial activities. There are many methods of remediation of heavy metals from e-waste including the classical physical, chemical and biological remediation methods, and the hybrid physico-chemical, physio-biological and chemical-biological remediation methods, as shown in Fig. 2 (Abalansa et al., 2021). Though various physical, chemical and biological methods are being used for the removal of metals; however, due to challenges (such as, *in-situ* failure, high cost, etc.) and in order to improve treatment efficiency, have encouraged the researchers to study the adoption of hybrid processes in diverse environmental mediums. The hybrid remediation techniques are the integration of two or more different ways to achieve a synergistic and successful attempt to remove/extract heavy metals from contaminated sites.

PHYSICAL REMEDIATION

Physical remediation is the process of correcting the problem by a number of physical means. The various physical remediation techniques that may be used for remediation of metals from e-waste include – thermal remediation, ion-exchange, adsorption by activated carbon, membrane filtration, solidification / stabilization, replacement by agri-waste, and removal by surfactants. These techniques are briefly summarized, along with their applicability, merits and limitations.

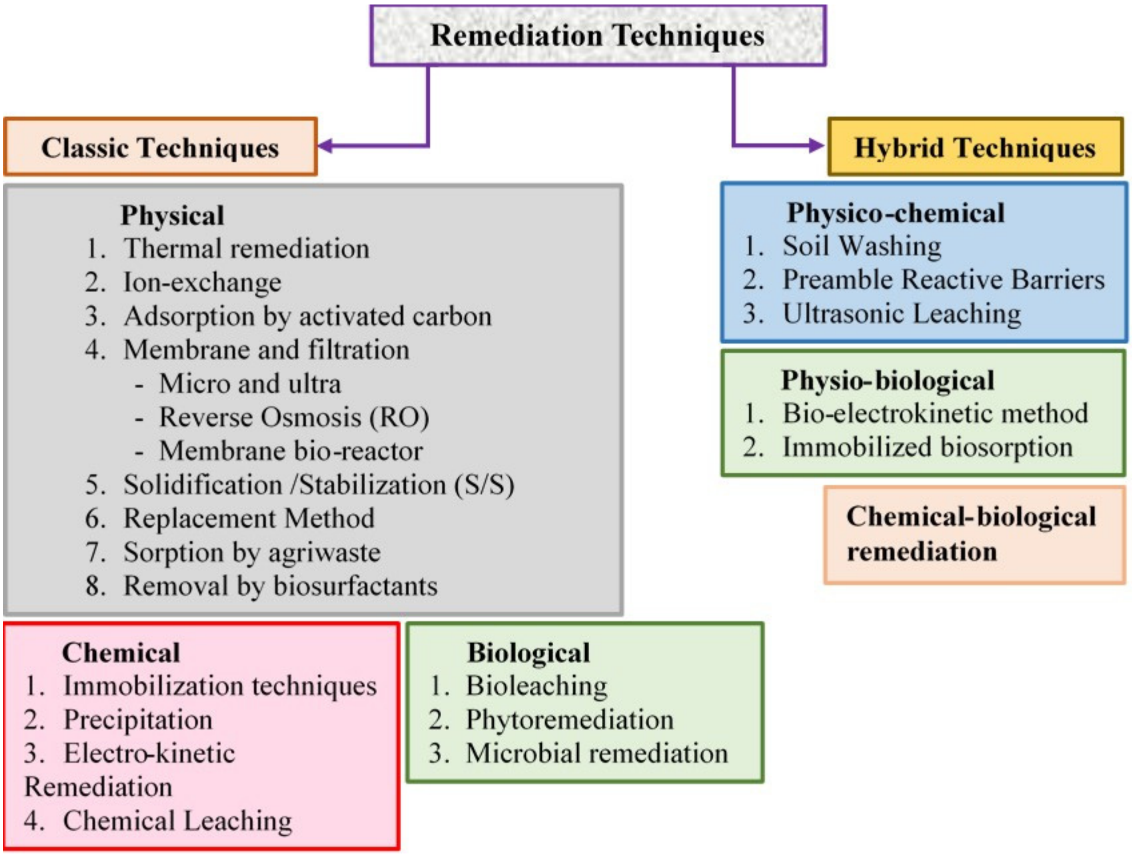

Fig. 2. Remediation Techniques for Heavy Metals

Thermal remediation

At temperatures between 300 and 400 degrees Celsius, thermal treatment can dramatically reduce metal toxicity (Li et al., 2012). Li et al. (2010) reported that the pollutants, like Hg and As, volatilized by heating them with steam, microwaves, and infrared radiation. At 280 °C, the thermal remediation could remove 95% of Cd, 85% of Zn, 77% of Cr and 97% Cu (Shi et al., 2013). Thermos-gravimetric approach at 550 °C for 1 hour removed about 99% of Hg as reported by Hseu et al. (2014). By *vitrification*, a type of thermal remediation, the contamination can be trapped and immobilized. This technique is primarily being used to remove organic and inorganic contaminants from polluted soil and sediments. Navarro et al. (2013) observed that Mn, Fe, Zn, Cu, Cr, Cd, Pb, Hg, As, and Se concentrations reduces by 90–100% at a temperature higher than 1,300°C by this technique. Thermal remediation is one of the most non-complex method for treating combined pollutants that ensures 99 % metal removal efficiency. Despite suitability, thermal remediation has limitations such as – it cannot be applied on pollutants which are in any other state except solid; requires huge energy inputs for achieving extremely high temperature; production of secondary pollutants in the form of gases that are toxic in nature; and waste generated needs to be re-recycled so as to completely get rid of the pollutants (Nejad et al., 2018; Shi et al., 2013).

Ion-exchange

For the removal of metals from wastewater, various synthetic and polymeric cationic resins (e.g., purolite C100) have been utilized (Feng et al., 2000). The degree of this process depends on different factors, such as ion size and valency, ion concentration, physico-chemical features of ion exchangers, and heat (Al-Enezi et al., 2004). Dabrowski et al. (2004) reported that the ion exchange process is more helpful in removing cadmium, lead, nickel, chromium, mercury, copper, and zinc from water pollutants where the attraction of exchangers for ions is Pb(II) > Cu(II) > Cd(II) > Zn(II). This remediation procedure can be used to remove metals from water without sacrificing high efficiency from liquid state of pollutants; however, the process is considerably more expensive than other methods of remediation.

Activated carbon adsorption method

Electrostatic interactions allow for the simple adsorption of metal ions from e-waste solutions (Ali et al., 2019). The parameters that govern the metal's adsorption include adsorbent surface area and absorbency, surface activity and size of the adsorbing species, metal and ion complex and pH (Periyasamy et al., 2020). Metal adsorption is commonly done with activated carbons due to high efficacy, flexibility and simplicity of design, easy operation and insensitivity to toxic heavy metals. Activated carbon made from peanut husk has been reported to be one of the strong adsorbent for heavy metals such as Pb, Cd, Ni, Zn from e-waste solutions, and capable of removing metals like As and Sb from copper-refining solutions of the e-waste recycling industry (Navarro & Alguacil, 2002). Though this is an efficient method for the pollutant removal, but the recovery of the metals from the adsorbents continues to remain difficult. Further, the process requires regeneration of adsorbent and extraction of some important metals is difficult.

Membrane and filtration

These include remediation techniques such as micro-filtration and ultra-filtration, reverse osmosis (RO) and membrane bioreactor (MBR). Out of these three processes, micro- and ultra-filtration being the most frequently used techniques having 70 to 80 % capacity to remove acid soluble heavy metals like As, Mo and Sb (Arevalo et al., 2013). Sandoval et al. (2019) reported that the ultra-filtration has been more effective in removal of Fe (92%) and Ni (62%). Reverse osmosis has been found to be useful for the separation process of metals mostly for Cu^{2+} ions and Cd^{2+} metal series present in e-waste, but costlier for Cd, Ni, Zn, etc (Reddy et al., 2014). Qdais & Moussa (2004) reported that RO is more efficient than nano-filtration and other membrane filtration methods. Conventional MBR has been reported as 50 % more efficient in metal removal in comparison to activated sludge (Battistoni et al., 2007); whereas, the electromagnetic MBR has been more popular for removing toxins from metals (Giwa & Hasan, 2015). However, the process has not been observed to be effective in metal ions with a lower valency (Wang et al., 2014). Though these techniques have good removal efficiency of heavy metals, but require higher cost and produce concentrated sludge.

Solidification / Stabilization (S/S)

There are certain organic or inorganic stabilizers which can be mixed with the metallic pollutants of e-waste to immobilize the metals. The organic stabilizers include leaves, saw dust, chitosan, sewage sludge, etc.; whereas, inorganic stabilizers include Fe/Mn oxides, cement, lime, fly ash etc. (Guo et al., 2006). S/S depends on many factors particularly the performance and efficiency of stabilizer. However, the process has its own set of limitations as its application has been limited in the detoxification of soil and sediment contamination only.

Replacement method

In the replacement method, the dissolved heavy metal ions in a polluted medium (solution) are made to come in contact with the more active metal so as to recover an ionized heavy metal by spontaneous electrochemical reduction to the elemental state, followed by oxidation of scarified metal (Peters & Shem, 1993). Generally, iron, aluminium or zinc are being used as an active/sacrificial metal for recovery of more precious and/or toxic metals, such as copper, chromium, etc. This method is mostly used for the soil sludge sediments and waste water and not much used for the e-waste, as it is economically viable for small scale treatment for small number of contaminants and limited to highly contaminated soil.

Sorption by agriwaste

Due to lower cost, the removal of heavy metals has been studied by sorption technique using agriwaste of different types. Renu et al. (2017) reported that agriwaste have lower removal capacity than the widely used activated carbon; however, chemically modified agriwastes has shown better results. The method is ecofriendly and cost effective as it uses agriwaste. However, it is applicable only for some functional groups and is pH dependent.

Biosurfactant remediation

Biosurfactants are surface-active substances produced by biological systems, primarily microbial. They dissolve metals in polluted material by releasing their hydrophilic and hydrophobic groups, and thus making them more accessible for cleanup (Ron & Rosenberg, 2001). The metallic compounds are eliminated by the surfactants due to the formation of complex compounds by reducing the surface tension (Mulligan & Wang, 2006). Biological detergents like *Sophorolipids* and *Rhamnolipids* have been reported to be quite effective in eliminating copper, nickel, zinc and cadmium from contaminated soils (Mulligan et al., 2001; Mulligan & Wang, 2006).

CHEMICAL REMEDIATION

It is an in-situ chemical process used to remove hazardous chemicals from the contaminated segment of environment. Chemical remediation utilizes various methods depending on the application, but mostly involve oxidation or reduction reactions with inorganic or organic compounds. The chemical remediation techniques used for remediation of metals from e-waste are briefly summarized as under:

Immobilization

In this remediation technique, the heavy metals or other pollutants are restricted to flow into the water or other environmental resources by adding modifications so as to trap the pollutants in the form of insoluble matter (Zhou et al., 2004). The process may be carried out in-situ or ex-situ immobilization executed in different situations with their own set of merits and demerits. The *in-situ* remediation uses fixing agent treatments for underground soil, and has significant public acceptance. The other benefits include low intrusiveness, rapidity, convenience and economical in reduced waste creation. However, Martin & Ruby (2004) reported that the pollutants may get activated if the soil's physical and chemical properties changes. Therefore, it requires continuous monitoring of the remediated site. *Ex-situ* technique is often applied in case of more contaminated soil posing serious threat to the environment. It is advantageous due to its easy applicability and lower investment. However, the byproducts or secondary pollutants generated during the process needs to be filled in the landfills in large quantity that makes the process a bit difficult to handle. Further, these secondary pollutants may be toxic due to their changed physics-chemical properties. Both these immobilization techniques have wide applicability for the removal of various heavy metals.

Precipitation

Precipitation is one of the most important and conventional methods of heavy metal removal, particularly in high metallic concentration. In precipitation process of remediation, the acid-base reactions are used to precipitate out the dissolved metal ions. Ok et al. (2011) reported that when the concentration of metalloid and pH both are higher in soil; precipitation seems to be the most suitable method. Aziz et al. (2008) have reported limestone as the most effective way to remove high concentration of metals.

Electro-kinetic remediation

The electro-kinetic remediation is a process that involves passing a weak alternating energy between a cathode and an anode that are both lodged in polluted sites (e.g., soil, sediments). In this process, ions and tiny charged particles are transferred between the electrodes in addition to water – every cation travel to negative, while all anions moves to positive and are thus separated by this mechanism (Mulligan et al., 2001). Electrophoresis, electric seepage, or electro-migration are being used to separate the metals present in the soil, resulting in a reduction in pollution (Yao et al., 2012). Li et al. (1996) reported a metal removal effectiveness of more than 96 % for copper and zinc by electrokinetic remediation. Due to its simple application and operation, the electrokinetic remediation technology is rapid and cost-effective process (Virkutyte et al., 2002). The key limiting component of this approach is soil pH fluctuation (Wang et al., 2007), along with high energy costs and formation of large particles.

Chemical leaching

In this method polluted materials are rinsed with chemical, freshwater, and other fluids or gases (Tampouris et al., 2001). Through ions exchange, precipitation, adsorption and chelation, metals in the polluted soil are moved to the liquid phase. Inorganic solvent, bonding ligands, and surfactants make up the majority of the leachate. Despite being biodegradables, organic leaching agents are generally ineffective. Alam et al. (2001) reported chemical leaching an environmentally friendly and cost-effective remediation approach for contaminated soil at 40 °C and 6.0 pH; and EDTA acid being the best compound for the formation of stable products at a wider pH range. However, recovering precious metals from chemical compounds and chelating agents remains difficult (Huang et al., 2011). Though chemical leaching process uses chemicals that makes it a point of environmental concern; but selective and low-cost chemical leaching techniques are required from a commercial standpoint.

Nano remediation

In recent years, nano-particles (1-100 nm in size) have been used as adsorbent material for the heavy metal remediation due to their excellent adsorbent characteristics and reported to have achieved 90 to 100 % removal of varying heavy metals (Al-Saad et al., 2012; Sheet et al., 2014; Mahmood et al., 2015). The nano-particles widely used in heavy metals removal include, iron-oxide, graphite oxide and silica (Yogeshwaran & Priya, 2019).

BIOLOGICAL REMEDIATION

Biological remediation or bioremediation is used to clean the pollutants and mineralize them using microbes, plants and animals. It is a technique for removing/converting harmful contaminants like heavy metals into less harmful substances, and/or removing toxic elements from the contaminated environment, or degrading organic substances and ultimate mineralization of organic substances into carbon dioxide, water, nitrogen gas, etc., employing dead or alive biomass. The process of bioremediation can be applied to soil and water media through *in-situ* and *ex-situ* techniques. It is an eco-friendly and cost-effective process for metal removal from the contaminated environment. Biological remediation includes bioleaching, phytoremediation and microbial remediation.

Bioleaching

It includes the process of emulsification of metals and semi-metals from deposits, and being widely used in energy sector like bio-hydrometallurgy or mining industry (Fonti et al., 2016).

Many known bacterial species such as *Acidothiobacillus ferroxidans, Thiobacillus thioxidans, Lycinicbacillus* have shown impressive remediation results (Pant et al., 2012; Ren et al., 2009). In bioleaching, *direct-* and *indirect-oxidation* activity is involved when microbes oxidises metals. In *direct-oxidation*, microbes attach to the metal salts with the help of extracellular polymer produced by the microbe itself to start its corrosion. Here, bacteria use its intracellular particular *oxidase* system and directly oxidise the metal sulphide and simultaneously producing H^+, which lowers the pH of the sludge, and the increased reduction potential results in the production of soluble sulphate (Kumar et al., 2014). The heavy metals present in the sludge progressively transition from the organic matter binding state towards the pure ionic state under these circumstances. In *indirect-oxidation*, the bacterial species reacts with the surrounding environment to transform available metal in inactive form. *Thiobacillus sp.* metabolites are often used in *indirect-oxidation* to solubilize metals from contaminated sludge. During the process, the low-valent sulphur compounds are converted into high-valent metal ions by the oxidation of the metal ions resulting in the oxidation of sludge accompanied by reduced pH. The form of the heavy metals in the sludge thus changes, and are liberated from the sludge as the reduction potential rises (Zeng et al, 2019a). Sharahabi-Farahani et al. (2014) showed that sulphur oxidizing bacteria produces sulphuric acid by reacting with pure sulphur making the metals inactive by reducing its pH. Narayanasamy et al. (2018) reported successful bioleaching of precious metals from E-waste using *A. niger*, and the use of the bacteria *Frankia* for the degradation of metals from printed circuit boards (Narayanasamy et al., 2021).

Phytoremediation

This method involves in collecting, neutralizing, and changing pollutants from a hazardous state to a lesser harmful state with the help of plants (Vidali, 2001; Khan et al., 2008). The intake or removal performance in phytoremediation depends upon various ecological elements/factors, like plant-microbe interaction, plant absorption capacity, relocation and resistance mechanisms, and plant's ability to leach. Phytoremediation is primarily being used for remediation of soil, water and sometimes sediments. Several plant species. such as *Cardaminopsis halleri* (Dietrich et al., 2021); *Bryophyllum*, *Pinnatum* and *Zea mays* (Mojiri, 2011); *Glycine max* (Aransiola et al., 2013); *Brassica junica* (Dalal & Dubey, 2011); *Beta* vulgaris (Sharma et al., 2007); and *Thlaspi caerulescens* (Zhao et al., 2003), have been reported to have a great performance in phytoremediation process.

Microbial remediation

Microbes play an important role in the process of bioremediation because of their great proficiency, easy processability and lack of secondary pollution from contaminated soil, silt and effluent water (Chen et al., 2005; De et al., 2008). Further, microbes can adapt quickly to extreme conditions such as hazardous chemicals, wide temperature variation, and presence or absence of oxygen Vidali (2001). However, Liu et al. (2017) reported the dependence of microbial remediation on various environmental and certain other factors, such as pH, heat, valance state of heavy metals, etc., for bioremediation of heavy metals using bacteria and fungi. Fungal strains such as *Aspergillus niger, Penicillium Chrysogenum* and several bacterial species like *Bacillus subtilis* and *Rhizopus sp.* have shown excellent performance in hazardous environment (Nakajima & Tsuruta, 2004). Liang et al. (2003) has reported that an increase in temperature may result in the enhancement of microbial metabolism along with the enzyme activity, and in turn further increases the process of bioremediation of heavy metals. Similarly, Bandowe et al. (2014) has also reported that the PAH and heavy metal bioremediation system being highly influenced by temperature because the bioavailability of PAHs and heavy metals improves by the solubility of these substances with increase in temperature. The bioremediation fate of PAHs and heavy metals has been reported to be significantly influenced by low molecular weight organic and humic acids, which are widely distributed in soils and ground water. By using ion exchange, surface adsorption and coordinate complexation, these acids can influence the behavior of heavy metals (Wu et al., 2003; Qin et al., 2004). Zhang et al. (2016) observed that co-existing of PAHs facilitate the adsorption of heavy metals in microbial remediation because both the pollutants can shift between weakly bound and firmly bound fractions. This is possibly due to rather uniform adsorption sites on the microorganisms or particles due to which the increased adsorption of heavy metals may limit the adsorption of other PAHs. However, Shen et al. (2006) reported that PAHs play an important role in microbial remediation process, and the transport of heavy metals on the bio-membrane can be altered when PAHs have a negative impact on microbial membranes. This is possible because PAHs may narcotize bacteria and interact with lipophilic bio-membrane components, thus changing the permeability of the bio-membrane and allowing heavy metals to enter microbial cells easily. Liu et al. (2017) observed that some heavy metals, such as Cu and Zn, are essential for the biological functions of bacteria, but others have no biological value and simply cause oxidative damage, denaturing organisms and reducing the capacity of microorganisms to remove heavy metals from the environment through bioremediation (such as Cr and Cd). Xu et al. (2012) reported that excessive amounts of any trace metal concentrations can become toxic to microbes, and thus hinder the bioremediation of metals. Higher concentrations of heavy metals have been regarded as harmful to microbes because they can impersonate active sites or denature protein structures, and stop enzymes or proteins from doing their jobs. Further, heavy metals can also interact with proteins' sulfhydryl groups and have anoxic effects on proteins or enzymes (Guo et al., 2010).

In spite of the fact that heavy metals are unbreakable, they can be made less toxic to the environment by chelating with chelators through chemical or physical remediation or by shifting the valence through a redox reaction that in turn produces secondary pollutants (Fan et al., 2008). Using the principal of valency shifting through redox reaction, mechanism of metal removing techniques of biological processes like phytoremediation and microbial remediation can be carried out effectively (Wu et al., 2010). Despite numerous advantages and high efficiency, the biological processes are time consuming and occupy a good amount of space. Further, in microbial remediation, the bonding between metal and microbial cell can be detachable and thus the metals can be released back in the environment when the microbe is dead or decomposed. Being environment friendly and economically viable, microbial remediation techniques make metal less toxic without any side effects on the environment (Ma et al., 2016).

PHYSIO-CHEMICAL REMEDIATION

Physio-chemical remediation methods are a blend of physical and chemical processes so as to harness better outcome by utilizing the merits of physical and chemical methods. The hybrid remediation processes can be applied to soil and water media through *in-situ* and *ex-situ* techniques. It is an eco-friendly and cost-effective process for metal removal from the contaminated environment. The hybrid physio-chemical remediation includes soil washing, permeable reactive barrier (PRBs) and ultrasonic leaching.

Soil washing

Soil surface washing method is a blend of physical and chemical processes, and is quite useful for removal of metallic pollutants from soil. In order to get better outcome, chelating agents like EDTA, sodium per-sulphate, citric acid, etc. are used to pull out metals like copper, nickel, zinc and lead. The process is influenced by particle diameter, sinking speed, specific gravity, surface composition, and magnetic characteristics of the contaminated soil (Wuanna & Okieimen, 2011). It is a widely used process as it requires less liquid for washing, cheap and efficient method for removing metals from soil. However, apart from the advantages, there are many limitations of this process which confines its use. These include – soil contaminated with heavily bonded metal, concentration of metal in the soil, exterior structure and moisture content in the soil (Dermont et al., 2008).

Permeable reactive barriers (PRBs)

PRB is a promising remediation approach for the integrated management of polluted water – acid mine drainage (AMD), groundwater or industrial wastewater that can be used *in-situ* or *ex-situ*. In PRB technology, a permanent, semi-permanent or replaceable reactive media is placed in the sub-surface across the flow path of a plume of polluted water under natural gradient so as to create a passive treatment system for decomposing, aggregating, sequestering or converting the pollutants present in polluted water flow. Typical reactant media contained in the PRBs include media designed for degrading volatile organics, chelators for immobilizing metals, or nutrients for microorganisms and with a porous material (such as sand) so as to enhance the flow of polluted water through the barrier.

Sorption process in *PRB* is simple and effective. Apak et al. (1998) suggested a mechanism wherein red mud acted as PRB to extract fine particles of Fe, Al. Si, Cd, TiO and OHs. In a similar study, Komnitsas et al. (2004) demonstrated the ability of red mud to remove metals from acid mine drainage (AMD). In both these studies, red mud has been discovered to have strong surface reactivity and the capacity to extract metals from acid mine drainage (AMD) and wastewater.

Biological barriers in PRB is often employed in designed passive bioreactors for the microbial conversion of hazardous chemicals. Several research studies reported ways to alter the redox conditions or supply substrates so as to assist naturally occurring bio-degradative systems (Barbaro & Barker, 2000; Fang et al., 2002). To enable the biodegradation of pollutants that pass through the biological barrier in PRB, biological reactive zones primarily depend on dissolved nutrients, nutrients injected into the area, and nutrients delivered to the area. Furthermore, it might be necessary to regularly replenish the media. This PRB method is low-performance and depends on nutrients for pollutant biodegradation. Also bio-clogging, which causes reduction in water saturation and hydraulic conductivity, may reduce the effectiveness of *in-situ* biological barriers in PRBs (Seki et al., 2006).

Ultrasonic leaching

The ultrasonic leaching method of metal remediation uses sonication and fragmentation along with an acidic solution and contaminated material. Dermont et al. (2008) reported the requirement of high acidic (sulphuric, nitric and hydrochloric acid) assist medium to maintain low pH (1.5-2.0) for ultrasonic leaching of metals. During the ultrasonic leaching process with the solution having pH of 0.75, almost 95% of Cu, 82% of Zn, and 87.3 % of Pb were solubilized as reported by Sharma et al. (2018). The metal removal efficiency further improves when combined with the electro-kinetic process. Despite high removal efficiency, the process has limited use as being applicable in low pH medium.

PHYSIO-BIOLOGICAL METHODS

Physio-biological remediation methods are a blend of physical and biological processes so as to improve the efficiency and versatility by utilizing the merits of both. The physio-biological hybrid remediation processes are environment-friendly and economical that can be applied to soil and water media through *in-situ* and *ex-situ* techniques. The hybrid physio-biological remediation includes bio-electrokinetic and immobilized biosorption techniques.

Bio-electrokinetic method

This method is most appropriate for remediating polluted soil, where microbiological and electrokinetic activities are combined to clean the waste. Due to the simultaneous dissolution of metals as an electrolyte and accumulation of metals on the electrode, the integrated approach of bioleaching and electrokinetic treatment seems favorable (Peng et al., 2011). This hybrid technique was applied by Peng et al. (2011) to remove Zn (up to 99 %) and Cu (up to 78.61%). The potential of this remediation technique needs to be explored along with the combination of different methods.

Immobilized biosorption

Soil or fermented wastes have several functional chemical groups (such as -CO, -NH, -OH, phosphate, sulphydryl, and sulphate) that are important for sorption process. Bio-sorbents may include living creatures (such crustaceans, seaweeds, and moss) and agricultural residues including defatted rice bran, whey, straw, sawdust. Activated sludge is a typical biomass rich in microorganisms, such as bacteria, yeast, fungi, and algae. Tiwari et al. (2017) used biomass of *Agrobacterium* capsuled with nanoparticles of iron oxide for lead adsorption, and reported quite encouraging results showing 192 mg/ gm of adsorption. The study by Rani et al. (2010) used immobilized isolates and dead cells of three different microbial strains of bacteria – *Bacillus sp.*, *Pseudomonas sp.* and *Micrococcus sp.* All strains displayed excellent biosorption for metals with immobilized isolates – biosorption by *Bacillus sp.* of Cu was 69.34 % in immobilized cell and 44.73 in dead cells; biosorption by *Pseudomonas sp.* of Cd was 90.41 % in immobilized cell and 86.66 % in dead cells; biosorption by *Micrococcus sp.* of Pb was 84.27 % in immobilized cell and 79.22 % in dead cells. Immobilized biosorption technology offers several advantages over conventional procedures, including improved bioremediation efficiency, better durability, and recyclability (Wang & Chen, 2009; Rani et al., 2010).

CHEMICAL-BIOLOGICAL REMEDIATION

Pradhan et al. (2017) has suggested that chemical and integrated biological method is more efficient for wastewater contaminated with metals. By adopting this hybrid technology based on the production of bacterially produced hydrogen sulphide, Luptakova et al. (2012) demonstrated sequential precipitation and removal of Cu^{2+}, Zn^{2+} and Fe^{3+} in the form of sulphides, and Al^{3+}, Fe^{2+} and Mn^{2+} in the form of hydroxides from acid mine drainage. Sharma & Malviya (2014) reported 62 % of total chromium removal from the given waste water by using *Fusarium chlamydosporium*. Although the fusion of chemical and biological methods for remediation have demonstrated notable out-comes; the major limitations include – longer incubation time, toxic secondary products, fluctuations in the process of biodegradation, and generation of large quantity of sludge (Lohner & Tiehm, 2009).

ENVIRONMENTALLY SOUND MANAGEMENT (ESM) OF E-WASTE

E-waste recycling is one of the sustainable solutions for dealing with the high tonnage of e-waste in the environment, both in developed and developing countries, and is critical in achieving a progressive circular economy (Isernia et al., 2019). India and some Asian, African and Latin American countries such as China, Vietnam, Kenya, Nigeria, Ghana, Mexico, Brazil, etc. are actively involved into the e-waste recycling business. Though formal e-waste recycling practices are beneficial to the environment and human health, they are not widely practiced especially in developing countries. Instead, the majority of recycling practices in developing countries are informal (Ignatuschtschenko, 2017), thus exposing the workers to e-waste hazards, as well as exposing the environment to e-waste contaminants.

To protect the human health and environment, formal scientific e-waste recycling regulations and facilities are required to be established that needs to conduct Environmentally Sound Management (ESM) of e-waste. ESM may be defined as “taking all practicable steps to ensure that used and/or end-of-life products and wastes are managed in a manner which will protect

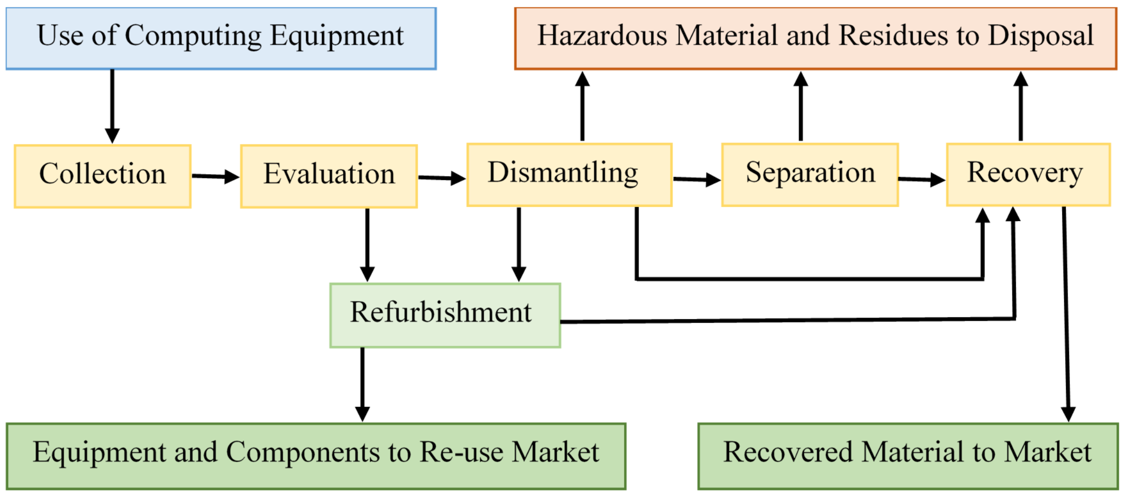

Fig. 3. Flowchart Depicting ESM Application in an E-waste Recycling Plant

human health and nature." To achieve this, there are seven designated ESM criteria as outlined herein:

- commitment of top management to a systematic approach;
- risk assessment;
- risk prevention and minimization;
- legal requirements;
- awareness, competency, and performance measurement;
- corrective action; and
- transparency and verification.

Garlapati (2016) has also suggested certain steps to be incorporated in recycling facilities to ensure ESM of e-waste, that has been presented in the form of a flow diagram for better illustration in Fig. 3. Recycling facilities needs to be updated adequately to reuse discarded EEE because costly resources should be extracted and dismantled only if they cannot be put to reuse. There are many other parts such as – capacitor, circuit boards and plastic, that can be reused (CII, 2006). Thermo-chemical treatment of such wastes is preferred as it provides enough efficient energy and material recycling; and the oil recovered from this can be used as fuel for burners (Kantarelis, 2011). The plastic waste from WEEE also serve as a raw material for hydrogen production through two-stage reaction system of pyrolysis–gasification (Acomb et al., 2013). While Gangadharan et al. (2015) suggested that a liquid crystal coated polaroid glass electrode collected form computer monitor and electrodes can be used in microbial fuel cell.

In order to avoid the increasing contaminated landfill sites and to protect the impact of e-waste on health and environment, more and more countries worldwide are coming up with new policies and regulations so to take care of their waste by working hand in hand with e-goods maker and jointly implementing Extended Producer Responsibility (EPR) laws (Garlapati, 2016; Wagner et al., 2022).

E-waste Policy and Regulations in India

For effective management of e-waste on a national scale, regulations and monitoring laws related to Extended Producer Responsibility (EPR) are essential. EPR includes tools like Life Cycle Assessment (LCA), Material Flow Analysis (MFA) and Multi Criteria Analysis (MCA) to control and regulate e-waste menace. The policy level acts, rules guidelines and initiatives in India regarding e-waste have been chronologically summarized in Table 3:

Table 3. Chronological Summary of E-waste related Acts, Rules and Guidelines in India

Act / Rules	Scope and Key Features
Atomic Energy Act, 1962	Deals with standards of controlling radioactive substances and cautious disposal of radioactive wastes.
The Hazardous Wastes (Management and Handling) Amendment Rules, 2003:	▪ For the first time, e-waste found mention in the regulations but without any detailed explanation. ▪ E-waste has been defined in Schedule-3 as "*Waste Electrical and Electronic Equipment (WEEE), along with all items, parts and components, and their subdivisions, excluding batteries under*", in synchronization with the Basal Convention definition.
Guidelines for Environmentally Sound Management (ESM) of E-waste, 2008	▪ E-waste categorized as per its configuration, emphasizing on the way it is treated and recycled. ▪ The concept of "*Extended Producer Responsibility (EPR)*" has been incorporated.
E-waste (Management and Handling) Rules, 2011	▪ The standards specified under Schedule-I apply to every manufacturer, purchaser, and management facility that handles the disassembly and recovery of e-waste. ▪ All machinery and consumables (EEE) manufacturing, as well as those items that are functional at the time of disposal, are subject to the implementation and operation of Schedule-I rules. ▪ Restrictions imposed on the use of dangerous substances in small quantities as well, including limits for heavy metals like Cd, Pb, Hg, hexavalent chromium, and PBDs. According to these regulations, the producer is required to maintain a record of the metals and compounds used. ▪ Any item or commercial product that has a substantial amount of uncertainty will be compared against Schedule-I components before a decision is made by competent authority. ▪ The machine used to manufacture electronic devices is not covered under these Rules; however, the residual items that it produces must be directed to the scrap yard where they must be repurposed entirely. ▪ The Central, and State Pollution Control Boards are the governing agencies in charge of overseeing the implementation of the Rules.
E- waste (Management) Amendment Rules, 2018	The amendments mainly focused on – ▪ Extended Producer Responsibility plans and targets, set offs, and transfer EPR in case of sale or transfer of assets by the producer; ▪ Levy of financial penalties on the manufacturer, producer, importer, transporter, refurbisher, dismantler and recycler for any violation of the provisions under these rules; and ▪ Withdraw or recall of the product from the market not complying the regulations within a reasonable period.
E-waste (Management) Rules, 2022	The new revised rules ensured Environmentally Sound Management (ESM) of e-waste with the inclusion of following provisions– ▪ The rules apply to every manufacturer, producer, refurbisher, dismantler and recycler involved in manufacture, sale, transfer, purchase, refurbishing, dismantling, recycling and processing of listed e-waste or EEE, including their components, consumables, parts and spares which make the product operational. ▪ The rules hall not apply to – waste batteries as covered under the Battery Waste Management Rules, 2022; packaging plastics as covered under the Plastic Waste Management Rules, 2016; micro enterprise as defined in the Micro, Small and Medium

Continued Table 3. Chronological Summary of E-waste related Acts, Rules and Guidelines in India

Act / Rules	Scope and Key Features
	Enterprises Development Act, 2006; and radio-active wastes as covered under the provisions of the Atomic Energy Act, 1962. ▪ Registration and certification of manufacturer, producer, refurbisher and recycler made mandatory for EEE under Extended Producer Responsibility Framework. Their responsibilities have also been defined and documented, along with the responsibilities of State Governments or Union Territories. ▪ Guidelines for reduction in the use of hazardous substances in the manufacture of EEE and their components or consumables or parts or spares. ▪ Guidelines for imposition and collection of environmental compensation on any entity in case of violation of any of the provision of these rules. ▪ Detailed categories with code of EEE including their components, consumables, parts and spares. ▪ Year wise e-waste recycling targets (by weight) to be achieved.
Battery Waste Management Rules, 2022	▪ Ensure ESM of waste batteries. ▪ Cover all types of batteries, including electric vehicle, portable, automotive, and industrial batteries. ▪ Based on the concept of EPR, where the producers are responsible for the collection and recycling/refurbishment of waste batteries, and the use of recovered materials from waste into new batteries. ▪ Establishment of environmental compensation fund.

CONCLUSION

The disposal and remediation techniques for polluted sites have been the key concerns in the field of environmentally sustainable management (ESM) of e-waste, particularly in developing countries wherein the indigenous and dumped e-waste is being treated by primitive recycling methods due to cheaper human resources and less stringent by laws coupled with source of income and employment for under-privileged in these countries. As a consequence, the overall environment is being degraded due to the increasing landfills/landscapes by e-waste. So, disposal and remediation techniques for polluted sites have been the key concerns in the field of environmentally sustainable management (ESM) of e-waste.

The present review revealed that of among all the classic and hybrid remediation techniques, the biological remediation techniques needs to be explored for metal removing from contaminated environment. The biological remediation techniques are not only eco-friendly but cost effective as well. Although, biological remediation is slow but they can be even more productive if given more time and research investments. The review also concludes that there is an imminent necessity of ESM by framing and implementing regulations and laws essentially incorporating Extended Producer Responsibility (EPR) in developing countries. The review of Indian scenario also revealed potential scope of startups for the sustainable recycling of e-waste to achieve healthy environment, employment and economic opportunities in developing countries. It is, therefore, recommended that the governments should encourage the startups for the sustainable recycling of e-waste (Cucchiella et al., 2015; Kaper et al., 2015) by supporting them technologically and financially.

ACKNOWLEDGEMENT

The authors would like to thank the KIRAN Division of Department of Science & Technology, Ministry of Science & Technology, GOI for the project grant under WOS-A scheme. The authors are also grateful to National Institute of Technology Kurukshetra (India) for providing all of the resources needed for the project under the WOS-A scheme.

GRANT SUPPORT DETAILS

The present research has been financially supported by the Department of Science & Technology, Ministry of Science & Technology, Government of India vide Sanction No. SR/WOS-A/LS-479/2018 (C) dated 17.09.2019, project entitled 'Removal of organic and inorganic toxins from electronic waste using isolated bacterial species and competent phytoremediation'.

CONFLICT OF INTEREST

The authors declare that there is not any conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy has been completely observed by the authors.

LIFE SCIENCE REPORTING

No life science threat was practiced in this research.

REFERENCES

Abalansa, S., Mahrad B.E., Icely J., & Newton A. (2021). Electronic waste, an environmental problem exported to developing countries: the good, the bad and the ugly. Sustainability, 13(9); 5302.

Acomb, J.C., Nahil, M.A., & Williams, P.T. (2013). Thermal processing of plastics from waste electrical and electronic equipment for hydrogen production. J. Anal. Appl. Pyrolysis., 103; 320–327.

Agate, A.D. (1996). Recent advances in microbial mining. World J. Microbiol. Biotechnol., 254; 487-495.

Alam, M.G.M., Tokunaga, S., & Maekawa, T. (2001). Extraction of arsenic in a synthetic arsenic contaminated soil using phosphate. Chemosphere, 43(8); 1035–1041.

Al-Enezi, G., Hamoda, M.F., & Fawzi, N. (2004). Ion exchange extraction of metals from wastewater sludges. J. Environ. Sci. Health A Tox Hazard Subst Environ Eng., 39(2); 455-464.

Ali, I.H., Al-Mesfer, M.K., Khan, M.I., Danish, M., & Alghamdi, M.M. (2019). Exploring adsorption process of lead (II) and chromium (VI) ions from aqueous solutions on acid activated carbon prepared from Juniperus procera leaves. Processes, 7(4); 217.

Al-Saad, K.A., Amr, M.A., Hadi, D.T., Arar, R.S., Al-Sultani, M.M., Abdulmalik, T.A., Alsahamary, N.M., & Al-Yahri, S.H. (2012). Iron oxide nanoparticles: applicability for heavy metal removal from contaminated water. Arab. J. Nuclear Sci. and Applications, 45(2), 335-346.

Amankwaa, E.F. (2013). Livelihoods in risk: exploring health and environmental implications of e-waste recycling as a livelihood strategy in Ghana. J. Mod. Afr. Stud., 51(4); 551–575.

Apak, R., Tutem, E., Hugul, M., & Hizal, J. (1998). Heavy metal cation retention by unconventional sorbents (red muds and fly ashes). Water Res., 32(2); 430–440.

Aransiola, S.A., Ijah, U.J.J., & Abioye, O.P (2013). Phytoremediation of lead polluted soil by *Glycine max* L. Applied and Environmental Soil Science, 2013; 1-7.

Arevalo, J., Ruiz, L.M., Perez, J., Moreno, B., & Gomez, M.A. (2013). Removal performance of heavy metals in MBR systems and their influence in water reuse. Water Sci. Technol., 67(4); 894-900.

ASSOCHAM (2016). India's e-waste growing at 30% per annum: assocham-cKinetics study. In: Bussiness Standards._

Awasthi, A.K., Hassan, M., Mishra, Y.M., Pandey, A.K., Tiwary, B.N., Kuhad, R.C., Gupta, V.K., & Thakur, V.K. (2019). Environmentally sound system for e-waste: biotechnological perspectives. CRBIOT., 1; 58-64.

Aziz, H.A., Adlan, M.N., & Ariffin, K.S. (2008). Heavy metals (Cd, Pb, Zn, Ni, Cu and Cr (III)) removal from water in Malaysia: post treatment by high quality limestone. Bioresour. Technol., 99(6); 1578–1583.

Balde, C.P., Forti, V., Gray, V., Kuehr, R., & Stegmann, P. (2017). The global e-waste monitor 2017: quantities, flows, and resources. United Nations University, International Telecommunication Union & International Solid Waste Association, Bonn/Geneva/Vienna.

Bandowe, B.A.M., Bigalke, M., Boamah, L., Nyarko, E., Saalia, F.K., & Wilcke, W. (2014). Polycyclic aromatic compounds (PAHs and oxygenated PAHs) and trace metals in fish species from Ghana (West Africa): bioaccumulation and health risk assessment. Environ. Int., 65; 135-146.

Barbaro, J.R., & Barker, J.F. (2000). Controlled field study on the use of nitrate and oxygen for bioremediation of a gasoline source zone. Bioremediat. J., 4(4); 259–270.

Battistoni, P., Cola, E., Fatone, F., Bolzonella, D., & Eusebi, A.L. (2007). Micropollutants removal and operating strategies in ultrafiltration membrane systems for municipal wastewater treatment: preliminary results. Ind. Eng. Chem. Res., 46(21); 6716-6723.

Ben, Y.J., Li, X.H., & Yang, Y.L., et al. (2014). Placental transfer of dechlorane plus in mother-infant pairs in an e-waste recycling area (Wenling, China). Environ. Sci. Technol., 48; 5187–5193.

Benassi, L., Zanoletti, A., Depero, L.E., & Bontempi, E. (2019). Sewage sludge ash recovery as valuable raw material for chemical stabilization of leachable heavy metals. J. Environ. Manage., 245; 464-470.

Bogdan-Martin, D. (2022). How Africa is leading the way in dealing with e-waste. The UN specialized agency for ICTs.

Brune, M.N., Goldizen, F.C., Neira, M., van den Berg, M., Lewis, N., King, M., Suk, W.A., Carpenter, D.O., Arnold, R.G., & Sly, P.D. (2013). Health effects of exposure to e-waste. Lancet Glob. Health, 1(2); e70.

Cao, J., Xu, X., Zhang, Y., Zeng, Z., Hylkema, M.N., & Huo, X. (2018). Increased memory T cell populations in Pb-exposed children from an e-waste recycling area. Sci. Total Environ., 616-617; 988–995.

Ceballos, M.C. & Dong, Z. (2016). The formal electronic recycling industry: challenges and opportunities in occupational and environmental health research. Environment International 95; 157-166.

Cesaro, A., Belgiorno, V., Vaccari, M., Jandric, A., Chung, T.D., Dias, M.I., Hursthouse, A., & Salhofer, S. (2017). A device-specific prioritization strategy based on the potential for harm to human health in informal WEEE recycling. Environ. Sci. Pollut. Res., 25; 683–692.

Chan, J.K., Xing, G.H., Xu, Y., Liang, Y., Chen, L.X., Wu, S.C., Wong, C.K.C., Clement, K.M., Leung., & Wong, M.H. (2007). Body loadings and health risk assessment of polychlorinated dibenzo-*p*-dioxins and dibenzofurans at an intensive electronic waste recycling site in China. Environ. Sci. Technol., 41; 7668 – 7674.

Chan, J.K.Y., Man, Y.B., Wu, S.C., & Wong, M.H. (2013a). Dietary intake of PBDEs of residents at two major electronic waste recycling sites in China. Sci. Total Environ., 463-464; 1138-1146.

Chan. J.K., & Wong, M.H. (2013b). A review of environmental fate, body burdens, and human health risk assessment of PCDD/Fs at two typical electronic waste recycling sites in China. Sci. Total Environ., 463-464; 1111–1123.

Chandna, P. & Deswal, S. (2005). E-pollution: a real dilemma. Journal of Pradushan Nirmulan, 2(4); 14-19.

Chen, A., Dietrich, K.N., Huo, X., & Ho, S. (2011). Developmental neurotoxicants in e-waste: an emerging health concern. Environ. Health Perspect., 119(4); 431–438.

Chen, D.H., Bi, X.H., Zhao, J.P., Chen, L.G., Tan, J.H., Mai, B.X., Shen, G., Fu, J., & Wong, M.H. (2009). Pollution characterization and diurnal variation of PBDEs in the atmosphere of an E-waste dismantling region. Environ. Pollut., 57; 1051–1057.

Chen, X.C., Wang, Y.P., Lin, Q., Shi, J.Y., Wu, W.X., & Chen, Y.X. (2005). Biosorption of copper (II) and zinc (II) from aqueous solution by Pseudomonas putida CZ1. Colloids Surf. B. Biointerfaces, 46(2); 101–107.

CII (2006). E-waste management, green business opportunities. Delhi: Confederation of Indian Industry; 1.

Collins, T., Kroehling, A., Kuehr, R., & de Roos, J. (2012). E-waste: annual gold, silver 'deposits' in new high-tech goods worth $21 billion +; less than 15% recovered. United Nations University: Tokyo, Japan.

Cordova-Pizarro, D., Aguilar-Barajas, I., Romero, D., & Rodriguez, C.A. (2019). Circular economy in the electronic products sector: material flow analysis and economic impact of cellphone e-waste in Mexico. Sustainability, 11(5); 1361.

Cucchiella, F., D'Adamo, I., Lenny Koh, S.C., & Rosa, P. (2015) Recycling of WEEEs: an economic assessment of present and future e-waste streams. Renew. Sustain. Energy Rev., 51; 263–272.

Dąbrowski, A., Hubicki, Z., Podkoscielny, P., & Robens, E. (2004). Selective removal of the heavy metal ions from waters and industrial wastewaters by ion-exchange method. Chemosphere, 56(2); 91–106.

Dalal, S., & Dubey, RC. (2011). Effects of crude and bioremediated thermal power plant effluents in *Brassica Juncea*. Soil and Sediment Contamination, 20; 329–336,

Daum, K., Stoler, J., & Grant, R.J. (2017). Toward a more sustainable trajectory for e-waste policy: a review of a decade of e-waste research in Accra, Ghana. Int. J. Environ. Res. Public Health, 14(2); 135.

De, J., Ramaiah, N., & Vardanyan, L. (2008). Detoxification of toxic heavy metals by marine bacteria highly resistant to mercury. Mar. Biotechnol., 10; 471–477.

Denogean, J.I. (2016). Electronic waste treatment in Mexico: viability and obstacles. Dissertation, Department of Earth and Environmental Engineering, Columbia University.

Dermont, G., Bergeron, M., Mercier, G., & Richer-Laflèche, M. (2008). Soil washing for metal removal: a review of physical/chemical technologies and field applications. J. Hazard. Mater., 152(1); 1-31.

Dietrich, C.C., Tandy, S., Murawskawlodarczyk, K., Banaś, A., Korzeniak, U., Seget, B., & Babst-Kostecka, A. (2021). Phytoextraction efficiency of *Arabidopsis halleri* is driven by the plant and not by soil metal concentration. Chemosphere, 285; 131437.

Eguchi, A., Kunisue, T., Wu, Q., Trang, P.T.K., Viet, P.H., Kannan, K., & Tanabe, S. (2014). Occurrence of perchlorate and thiocyanate in human serum from e-waste recycling and reference sites in Vietnam: association with thyroid hormone and iodide levels. Arch. Environ. Contam. Toxicol., 67; 29–41.

Eguchi, A., Nomiyama, K., Tue, N.M., Trang, P.T.K, Viet, P.H., Takahashi, S., & Tanabe, S. (2015). Residue profiles of organohalogen compounds in human serum from e-waste recycling sites in North Vietnam: association with thyroid hormone levels. Environ Res., 137; 440–49.

European Parliament (2003). Directive 2002/96/EC of the European parliament and of the Council of 27 January 2003 on waste electrical and electronic equipment (WEEE). Off. J. Eur. Union, L37; 24–38.

European Parliament (2012). Directive 2012/19/EU of the European parliament and of the Council of 4 July 2012 on waste electrical and electronic equipment (WEEE). Off. J. Eur. Union, L197; 38-71

Fan, T., Liu, Y., Feng, B., Zeng, G., Yang, C., Zhou, M., Zhou, H., Tan, Z., & Wang, X. (2008). Biosorption of cadmium (II), zinc (II) and lead (II) by *Penicillium simplicissimum*: isotherms, kinetics and thermodynamics. J. Hazard. Mater., 160; 655-661.

Fang, Y., Hozalski, R.M., Clapp, L.W., Novak, P.J., & Semmens, M.J. (2002). Passive dissolution of hydrogen gas into groundwater using hollow-fiber membranes. Water Res., 36(14); 3533–3542.

Feng, D., Aldrich, C., & Tan, H. (2000). Treatment of acid mine water by use of heavy metal precipitation and ion exchange. Miner. Eng., 13(6); 623–642.

Fonti, V., Dell'Anno, A., & Beolchini, F. (2016). Does bioleaching represent a biotechnological strategy for remediation of contaminated sediments? Sci. Total Environ., 563-564; 302–319.

Forti, V., Balde, C.P., Kuehr, R., & Bel, G. (2020). The global e-waste monitor: quantities, flows, and the circular economy potential. United Nations University, Tokyo, Japan.

Freeman, M.H. (1989). Standard handbook of hazardous waste treatment and disposal. McGraw-Hill Company, USA.

Fu, J., Zhang, H., Zhang, A., & Jiang, G. (2018). E-waste recycling in China: a challenging field. Environ. Sci. Technol., 52(12); 6727–6728.

Gaidajis, G., Angelakoglou, K., & Aktsoglou, D. (2010). E-waste: environmental problems and current management. J. Eng. Sci. Technol. Rev., 3(1); 193–199.

Gangadharan, P., Nambi, I.M., & Senthilnathan, J. (2015). Liquid crystal polaroid glass electrode from e-waste for synchronized removal/recovery of Crþ6 from wastewater by microbial fuel cell. Bioresour. Technol., 195; 96–101.

Garlapati, V.K. (2016). E-waste in India and developed countries: management, recycling, business and biotechnological initiatives. Renew. Sustain. Energy Rev., 54; 874-888.

Gill, P. (2019). Developing countries like India bear the brunt of global e-waste. Business Insider India.

Giwa, A., & Hasan, S.W. (2015). Numerical modeling of an electrically enhanced membrane bioreactor (MBER) treating medium-strength wastewater. J. Environ. Manage., 164; 1–9.
Hinchliffe, D., & Gunsilius, E. (2017). Building the link: leveraging formal-informal partnerships in the Indian e-waste sector. International Zusammenarbeit (GIZ) GmH, Frankfurt.
Grant. K., Goldizen, F.C., Sly, P.D., Brune, M.N., Neira, M., van den Berg, M., & Norman, R.E. (2013). Health consequences of exposure to e-waste: a systematic review. Lancet Glob. Health, 1(6); e350-e361.
Greenpeace (2019). China's e-waste worth $23.8 billion by 2030. Greenpeace East Asia.
Guo, G., Zhou, Q., & Ma, L.Q. (2006). Availability and assessment of fixing additives for the in situ remediation of heavy metal contaminated soils: A review. Environ. Monit. Assess., 116; 513–528.
Guo, L.C., Yu, S., Wu, D., et al. (2019). Disruption of thyroid hormone regulated proteins and gene expression by polychlorinated biphenyls, polybrominated diphenyl ethers and new flame retardants in residents of an e-waste region. Environ. Pollut., 254; 112925.
Guo, Y., Huo, X., Li, Y., Wu, K., Liu, J., Huang, J., Zheng, G., Xiao, Q., Yang H., Wang, Y., Chen, A., & Xu, X. (2010). Monitoring of lead, cadmium, chromium and nickel in placenta from an e-waste recycling town in China. Sci. Total Environ., 408; 3113-3117.
Heacock, M., Kelly, C.B., & Suk, W.A. (2016). E-waste: the growing global problem and next steps. Rev. Environ. Health, 31; 131–35.
Hseu, Z.-Y., Huang, Y.-T., & Hsi, H.C. (2014). Effects of remediation train sequence on decontamination of heavy metal-contaminated soil containing mercury. J. Air Waste Manag. Assoc., 64(9); 1013–1020.
Huang, K., Inoue, K., Harada, H., Kawakita, H., & Ohto, K. (2011). Leaching of heavy metals by citric acid from fly ash generated in municipal waste incineration plants. J. Mater. Cycle Waste Manag., 13; 118–126.
Huo, X., Dai, Y., Yang, T., Zhang, Y., Li, M., & Xu, X. (2019a). Decreased erythrocyte CD44 and CD58 expression link e-waste Pb toxicity to changes in erythrocyte immunity in preschool children. Sci. Total Environ., 664; 690–697.
Huo, X., Wu, Y., Xu, L., Zeng, X., Qin, Q., & Xu, X. (2019b). Maternal urinary metabolites of PAHs and its association with adverse birth outcomes in an intensive e-waste recycling area. Environ. Pollut., 245; 453–61.
Ignatuschtschenko, E. (2017). E-waste management in China: bridging the formal and informal sectors. J. Chin. Gov., 2(4); 385–410.
ILO (2019). From waste to jobs: Decent work challenges and opportunities in the management of e-waste in India. International Labour Office, Sectoral Policy Department: Geneva, Switzerland.
Isernia, R., Passaro, R., Quinto, I., & Thomas, A. (2019). The reverse supply chain of the e-waste management processes in a circular economy framework: evidence from Italy. Sustainability, 11(8); 2430.
Isimekhai, K.A. (2017). Environmental risk assessment for an informal e-waste recycling site in Lagos State, Nigeria. Middlesex University, London, UK.
Islam, A., Ahmed, T., Awual, M.R., Rahman, A., Sultana, M., Aziz, A.A., Monir, M.U., Teo, S.H., & Hasan, M. (2020). Advances in sustainable approaches to recover metals from e-waste-a review. J. Clean. Prod., 244; 118815.
Islam, M.T., & Huda, N. (2019). E-waste in Australia: generation estimation and untapped material recovery and revenue potential. Journal of Cleaner Production, 237; 117787.
Joon, V., Shahrawat, R., & Kapahi, M. (2017). The emerging environmental and public health problem of electronic waste in India. J. Health Pollut., 7(15); 1–7.
Kalia, P., Zia, A., & Mladenovic, D. (2022). Examining country development indicators and e-waste under the moderating effect of country development levels and e-waste policy. International Journal of Quality & Reliability Management. 39(7); 1601-1616.
Kaminsky, J.A. (2016). Cultured construction: global evidence of the impact of national values on piped-to-premises water infrastructure development. Environmental Science & Technology, 50(14); 7723-7731.
Kantarelis, E., Yang, W., Blasiak, W., Forsgren, C., & Zabaniotou, A. (2011). Thermochemical treatment of e-waste from small household appliances using highly preheated nitrogen-thermogarvimetric investigation and pyrolysis kinetics. Appl. Energy, 88(3); 922–929.
Kasper, A.C., Gabriel, A.P., de Oliveira, E.L.B., Juchneski, N.C.F., & Veit, H.M. (2015). Electronic

waste recycling techniques. *In:* Veit, H., & Bernardes, A.M. (eds) Electronic waste. Springer International Publishing; 87-127.

Khan, S., Cao, Q., Zheng, Y.M., Huang, Y.Z., & Zhu, Y.G. (2008). Health risks of heavy metals in contaminated soils and food crops irrigated with wastewater in Beijing, China. Environ. Pollut., 152(3); 686–692.

Komnitsas, K., Bartzas, G., & Paspaliaris, I. (2004). Efficiency of limestone and red mud barriers: Laboratory column studies. Mineral., Eng. 17(2); 183–194.

Kopacek, B. (2021). There's much value in store in e-waste. Bussinessline.

Kumar, K., Suthar, S., Dastidar, M.G., & Sreekrishnan, T.R. (2014). Bioleaching of heavy metals from textile sludge by indigenous sulfur-and-iron-oxidizing microorganisms using elemental sulfur and ferrous sulfate as energy sources: a comparative study. Geomicrobiology Journal, 31(10); 847-854.

Ladou. J., & Lovegrove, S. (2008). Export of electronics equipment waste. Int. J. Occup. Environ. Health, 14; 1-10.

Leur, A.V., & Walter, D. (2019). From waste to jobs: decent work challenges and opportunities in the management of e-waste in India. International Labour Office (ILO), Sectoral Policies Department, Geneva, Switzerland.

Li, J., Zhang, G.N., & Li, Y. (2010). Review on the remediation technologies of POPs. Hebei. Environ. Sci., 65; 1295–1299.

Li, L., Xu, Z.R., Zhang, C., Bao, J., & Dai, X. (2012). Quantitative evaluation of heavy metals in solid residues from sub-and super-critical water gasification of sewage sludge. Bioresour. Technol., 121; 169–175.

Li, M., Huo, X., Pan, Y., Cai, H., Dai, Y., & Xu, X. (2018). Proteomic evaluation of human umbilical cord tissue exposed to polybrominated diphenyl ethers in an e-waste recycling area. Environ. Int., 111; 362–71.

Li, Z., Yu, J.W., & Neretnieks, I. (1996). A new approach to electrokinetic remediation of soils polluted by heavy metals. J. Contam. Hydrol., 22(3-4); 241–253.

Liang, C., Das, K., & McClendon, R. (2003). The influence of temperature and moisture contents regimes on the aerobic microbial activity of a biosolids composting blend. Bioresour. Technol., 86; 131-137.

Liddle, C. (2013). Principles of monitoring postoperative patients. Nursing times, 109; 24-26.

Liu, S.H., Zeng, G.M., Niu, Q.Y., Liu, Y., Zhou, L., Jiang, L.H., Tan, X.F., Xu, P., Zhang, C., & Cheng, M. (2017). Bioremediation mechanisms of combined pollution of PAHs and heavy metals by bacteria and fungi: a mini review. Bioresour Technol., 224; 25-33.

Liu, W., Huo, X., Liu, D., Zeng, X., Zhang, Y., & Xu, X. (2014). S100β in heavy metal-related child attention-deficit hyperactivity disorder in an informal e-waste recycling area. Neurotoxicology, 45; 185–191.

Lohner, S.T., & Tiehm, A. (2009). Application of electrolysis to stimulate microbial reductive PCE dechlorination and oxidative VC biodegradation. Environ. Sci. Technol., 43(18); 7098–7104.

Luptakova, A., Ubaldini, S., Macingova, E., Fornari, P., & Giuliano, V. (2012). Application of physical–chemical and biological–chemical methods for heavy metals removal from acid mine drainage. Process Biochem., 47(11); 1633–1639.

Ma, Y., Rajkumar, M., Zhang, C., & Freitas, H. (2016). Beneficial role of bacterial endophytes in heavy metal phytoremediation. J. Environ. Manage., 174; 14-25.

Magalini, F., Kuehr, R., & Balde, C.P. (2015). E-waste in Latin America: statistical analysis and policy recommendations. United Nations University – Institute for the Advanced Study of Sustainability; 1-35.

Mahmoud, A.M., Ibrahim, F.A., Shabaan, S.A., & Youssef, N.A. (2015). Adsorption of heavy metal ion from aqueous solution by nickel oxide nano catalyst prepared by different methods. Egyption J. Petroleum, 24; 27-35.

Manhart, A., Osibanjo, O., Aderinto, A., & Prakash, S. (2011). Informal e-mawaste management in Lagos, Nigeria–socio-economic impacts and feasibility of international recycling co-operations. Final Rep. Compon., 3; 1–129.

Manomaivibool, P. (2009). Extended producer responsibility in a non-OECD context: the management of waste electrical and electronic equipment in India. Resour. Conserv. Recycl., 53; 136–144.

Martin, T.A., & Ruby, M.V. (2004). Review of in situ remediation technologies for lead, zinc, and cadmium in soil. Remediat. J. Eviron. Cleanup Cost. Technol. Tech., 14(3); 35-53.

Matsukami, H., Tue, N.M., Suzuki, G., et al. (2015). Flame-retardant emission from e-waste recycling operation in northern Vietnam: environmental occurrence of emerging organophosphorus esters used as alternatives for PBDEs. Sci. Total Environ., 514; 492–99.

Mejame, P.P.M., Jung, D.Y., Lee, H., Lee, D.S., & Lim, S.R. (2020). Effect of technological developments for smartphone lithium battery on metal-derived resource depletion and toxicity potentials. Resources, Conservation and Recycling, 158; 104797.

Migliano, J.E.B., Demajorovic, J., & Xavier, L.H. (2014). Shared responsibility and reverse logistics systems for e-waste in Brazil. J. Oper. Supply Chain. Manag., 7(2); 91–109.

MoEFCC (2003). The hazardous wastes (management and handling) amendment rules, 2003. Ministry of Environment, Forest and Climate Change, Government of India.

MoEFCC (2008). Guidelines for environmentally sound management of e-waste, 2008. Ministry of Environment, Forest and Climate Change, Government of India.

MoEFCC (2011). E-waste (management and handling) rules, 2011. Ministry of Environment, Forest and Climate Change, Government of India.

MoEFCC (2018). E-waste (management) amendment rules, 2018. Ministry of Environment, Forest and Climate Change, Government of India.

MoEFCC (2022). E-waste (management) rules, 2022. Ministry of Environment, Forest and Climate Change, Government of India.

MoEFCC (2022). Battery waste management rules, 2022. Ministry of Environment, Forest and Climate Change, Government of India.

Mojiri, A. (2011). The potential of corn (*Zea mays*) for phytoremediation of soil contaminated with cadmium and lead. Journal of Biological and Environmental Sciences, 5(13); 17-22.

Mulligan, C.N., & Wang, S. (2006). Remediation of a heavy metal-contaminated soil by a rhamnolipid foam. Eng. Geol., 85(1-2); 75–81.

Mulligan, C.N., Yong, R.N., & Gibbs, B.F. (2001). Remediation technologies for metal-contaminated soils and groundwater: an evaluation. Eng. Geol., 60(1-4); 193–207.

Nakajima, A., & Tsuruta, T. (2004). Competitive biosorption of thorium and uranium by Micrococcus luteus. J. Radioanal. Nucl. Chem., 260(1); 13–18.

Narayanasamy, M., Dhanasekaran, D., & Thajjudin, N. (2021). Bioremediation of noxious metals from e-waste printed circuit boards by *Frankia*. Microbiol. Res., 245; 126707.

Narayanasamy, M., Dhanasekaran, D., Vinothini, G., & Thajjudin, N. (2018). Extraction and recovery of precious metals from electronic waste printed circuit boards by bioleaching acidiophilic fungi. Int. J. Environ. Sci. Technol., 15; 119-132.

Navarro, A., Cardellach, E., Canadas, I., & Rodriguez, J. (2013). Solar thermal vitrification of mining contaminated soils. Int. J. Miner. Process., 119; 65–74.

Navarro, P., & Alguacil, F.J. (2002). Adsorption of antimony and arsenic from a copper electrorefining solution onto activated carbon. Hydrometallurgy, 66; 101–105.

Needleman, H. (2009). Low level lead exposure: history and discovery. Ann. Epidemiol., 4; 235-238.

Nejad, Z.D., Jung, M.C., & Kim, K.H. (2018). Remediation of soils contaminated with heavy metals with an emphasis on immobilization technology. Environ. Geochem. Health, 40; 927-953.

Nnorom, I.C., & Odeyingbo, O.A. (2020). Electronic waste management practices in Nigeria. Butterworth-Heinemann: Oxford, UK; 323–354.

Obaje, S.O. (2013). Electronic waste scenario in Nigeria: issues, problems and solutions. Int. J. Eng. Sci. Invent., 2(11); 31–36.

Ok, Y.S., Lim, J.E., & Moon, D.H. (2011). Stabilization of Pb and Cd contaminated soils and soil quality improvements using waste oyster shells. Environ. Geochem. Health, 33; 83-91.

Pant, D., Joshi, D., Upreti, M.K., & Kotnala, R.K. (2012). Chemical and biological extraction of metals present in E waste: A hybrid technology. Waste Manag., 32; 979-990.

Pariatamby, A., & Victor, D. (2013). Policy trends of e-waste management in Asia. J Mater Cycles Waste Manag, 15; 411–419.

Pathak, A., Dastidar, M.G., & Sreekrishnan, T.R. (2009). Bioleaching of heavy metals from sewage sludge: A review. J. Environ. Manage., 90(8); 2343-2353.

Pathak, A., Singh, P., Dhama, P., Dastidar, M.G., Kim, D.J., & Heyes, G. (2014). Comparative study on simultaneous leaching of nutrients during bioleaching of heavy metals from sewage sludge using indigenous iron and sulphur oxidising microorganisms. Can. Metall. Q., 53(1); 65-73.

Peng, G., Tian, G., Liu, J., Bao, Q., & Zang, L. (2011). Removal of heavy metals from sewage sludge with a combination of bioleaching and electrokinetic remediation technology. Desalination 271(1-

3); 100–104.
Periyasamy, S., Kumar, I.A., & Viswanathan, N. (2020). Activated carbon from different waste materials for the removal of toxic metals. *In:* Naushad, M., & Lichtfouse, E. (Eds.), Green Materials for Wastewater Treatment. Springer International Publishing, Cham., 38; 47–68.
Perkins, D.N., Drisse, M.N.B., Nxele, T., & Sly, P.D. (2014). E-waste: a global hazard. Ann. Glob. Health, 80(4); 286–295.
Peters, R.W., & Shem, L. (1993). Separation of heavy metals: removal from industrial wastewaters and contaminated soil. In: Symposium on emerging separation technologies for metals and fuels. Palm Coast, FL, United States.
Pourhossein, F., & Mousavi, S.M. (2018). Enhancement of copper, nickel, and gallium recovery from LED waste by adaptation of *Acidithiobacillus ferrooxidans*. Waste Manage., 79; 98–108.
Pradhan, D., Sukla, L.B., Sawyer, M., Rahman, & P.K. (2017). Recent bioreduction of hexavalent chromium in wastewater treatment: A review. J. Ind. Eng. Chem., 55; 1–20.
Puckett, J., Byster, I., Westerrelt, S., Gutierrez, R., Davis, S., Hussain, A., & Madhumita, D.D. (2002). The Basel Action Network (BAN) and Silicon Valley Toxics Coalition (SVTC) with Toxics Link India, SCOPE Pakistan and Greenpeace China E-Exporting Harm: The High-Tech Trashing of Asia. Basel Action Network, USA.
Pwamang, J.A. (2013). Government policy and initiatives on e-waste in Ghana. *In:* Proceedings of the 3rd Annual Global E-Waste Management (GEM) Network Meeting, USA.
Qdais, H.A., & Moussa, H. (2004). Removal of heavy metals from wastewater by membrane processes: a comparative study. Desalination, 164(2); 105–110.
Qin, F., Shan, X.Q., & Wei, B. (2004). Effects of low-molecular-weight organic acids and residence time on desorption of Cu, Cd, and Pb from soils. Chemosphere, 57; 253-263.
Qu, W.Y., Bi, X.H., Sheng, G.Y., Lu, S.Y., Fu, H., Yuan, J., & Li, L. (2007). Exposure to polybrominated diphenyl ethers among workers at an electronic waste dismantling region in Guangdong, China. Environ. Int., 33; 1029–1034.
Rani, M.J., Hemambika, B., Hemapriya, J., & Kannan, V.R. (2010). Comparative assessment of heavy metal removal by immobilized and dead bacterial cells: A biosorption approach. Afr. J. Environ. Sci. Technol., 4(2); 77-83.
Reddy, K.R., Xie, T., & Dastgheibi, S. (2014). Evaluation of biochar as a potential filter media for the removal of mixed contaminants from urban storm water runoff. J. Environ. Eng., 140(12); 04014043.
Ren, W.X., Li, P.J., Geng, Y., & Li, X.J., (2009). Biological leaching of metals from a contaminated soil by *Aspergillus niger*. J. Hazard. Mater. 167; 164–169.
Renu, Agarwal, M., Singh, K., Upadhyaya, S., & Dohare, R.K. (2017). Removal of heavy metals from wastewater using modified agricultural adsorbents. Materials Today, 4; 10534-10538.
Robinson, B.H. (2009). E-waste: an assessment of global production and environmental impacts. Sci. Total environ., 408; 183-191.
Ron, E.Z., & Rosenberg, E. (2001). Natural roles of biosurfactants: Minireview. Environ. Microbiol., 3(4); 229–236.
Sandoval, A.D.O., Briao, V.B., Fernandes, V.M.C., Hemkemeier, A., Friedrich, & M.T. (2019). Stormwater management by microfiltration and ultrafiltration treatment. J. Water Process. Eng., 30; 100453.
Sansotera, M., Navarrini, W., Talaeemashhadi, S., & Venturini, F. (2013). Italian WEEE management system and treatment of end-of-life cooling and freezing equipments for CFCs removal. Waste Management, 33(6); 1491-1498.
Scheutz, C., Mosbaek, H., & Kjeldsen P. (2004). Attenuation of methane and volatile organic compounds in landfill soil covers. J. Environ. Qual., 33; 61–71.
Seki, K., Thullner, M., Hanada, & J., Miyazaki, T. (2006). Moderate bioclogging leading to preferential flow paths in biobarriers. Groundw. Monit. Remediat., 26(3); 68–76.
Shahrabi-Farahani, M., Yaghmaei, S., Mousavi, S., & Amiri, F. (2014). Bioleaching of metals from a petroleum spent catalyst using *Acidithiobacillus thiooxidans* in a slurry bubble column bioreactor. Sep. Purif. Technol., 132; 41–49.
Sharma, R.K., Agrawal, M., & Marshal, F. (2007) Heavy metal contamination of soil and vegetables in suburban areas of Varanasi, India. Ecotoxicology and Environmental Safety, 66(2); 258-66.
Sharma, S., & Malaviya, P. (2014). Bioremediation of tannery wastewater by chromium resistant fungal

isolate *Fusarium chlamydosporium* SPFS2-g. Curr. World Environ. 9(3); 721-727.
Sharma, S., Tiwari, S., Hasan, A., Saxena, V., & Pandey, L.M. (2018). Recent advances in conventional and contemporary methods for remediation of metal-contaminated soils. 3 Biotech, 8; 216.
Sheet, I., Kabbani, A., & Holail, H. (2014). Removal of heavy metals using nano structured graphite oxide, silica nano-particles and silica/graphite oxide composite. *In:* International Conference of Technologies and Materials for Renewable Energy, Environment and Sustainability (TMREES), 14(50); 130-138.
Shen, G., Lu, Y., & Hong, J. (2006). Combined effect of heavy metals and polycyclic aromatic hydrocarbons on *urease* activity in soil. Ecotoxicol. Environ. Saf., 63; 474-480.
Shi, W., Liu, C., Ding, D., Lei, Z., Yang, Y., Feng, C., & Zhang, Z. (2013). Immobilization of metals in sewage sludge by using subcritical water technology. Bioresour. Technol., 137; 18–24.
Sieff, K. (20121). The world is drowning in ever-growing mounds of garbage. The Washington Post.
Sotelo, S.C., Ojeda-Benitez, S., Velázquez-Victorica, K.I., Soto, N., Cueto, R.G., Taboada-González, P., & Aguilar-Virgen, Q. (2016). Electronic waste in Mexico-challenges for sustainable management. *In:* E-waste in Transition, Chapter 5; 95-119.
Sovacool, B.K. (2019). Toxic transitions in the lifecycle externalities of a digital society: the complex afterlives of electronic waste in Ghana. Resour. Policy, 64; 101459.
Streicher-Porte, M., Widmer, R., Jain, A., Bader, H.P., Scheidegger, R., & Kytzia, S. (2005). Key drivers of the e-waste recycling system: assessing and modelling e-waste processing in the informal sector in Delhi. Environmental Impact Assessment Review, 25; 472 – 491.
Sullivan, J. (2014). Trash or treasure: global trade and the accumulation of e-waste in Lagos, Nigeria. Afr. Today, 61(1); 89–112.
Tampouris, S., Papassiopi, N., & Paspaliaris, I. (2001). Removal of contaminant metals from fine grained soils, using agglomeration, chloride solutions and pile leaching techniques. J. Hazard. Mater., 84(2-3); 297–319.
Tiwari, S., Hasan, A., & Pandey, L.M. (2017). A novel bio-sorbent comprising encapsulated *Agrobacterium fabrum* (SLAJ731) and iron oxide nanoparticles for removal of crude oil co-contaminant, lead Pb (II). J. Environ. Chem. Eng., 5(1); 442–452.
Tsydenova, N., & Heyken, M. (2018). Formal and informal e-waste collection in Mexico City. *In:* Cascade Use in Technologies, Springer, Berlin/Heidelberg, Germany; 30–37.
Tsydenova, O., & Bengtsson, M. (2011). Chemical hazards associated with treatment of waste electrical and electronic equipment. Waste Manag., 31; 45–58.
Turaga, R.M.R., Bhaskar, K., Sinha, S., Hinchliffe, D., Hemkhaus, M., Arora, R., Chatterjee, S., Khetriwal, D.S., Radulovic, V., & Singhal, P. (2019). E-waste management in India: issues and strategies. Vikalpa, 44(3); 127–162.
UNEP (2012). United Nation Environment Programme Report: e-waste volume III: WEEE/E-waste "Take Back System". Division of Technology, Industry and Economics, International Environmental Technology Centre, Osaka.
Vats, M.C., & Singh, S.K. (2015). Assessment of gold and silver in assorted mobile phone printed circuit boards (PCBs). Waste Manage., 45; 280–288.
Vidali, M. (2001). Bioremediation - an overview. Pure Appl. Chem., 73(7); 1163–1172.
Virkutyte, J., Sillanpaa, M., & Latostenmaa, P. (2002). Electrokinetic soil remediation – critical overview. Sci. Total Environ., 289(1-3); 97–121.
Wagner, M., Balde C.P., Luda, V., Nnorom, I.C., Kuehr, R., & Iattoni, G. (2022). Regional e-waste monitor for Latin America: results for the 13 countries participating in project UNIDO-GEF 5554. UNI/UNITAR, Bonn, Germany.
Wang, F., Huisman, J., Marinelli, T., Zhang, Y., & van Ooyen, S.V. (2008). Economic conditions for formal and informal recycling of e-waste in China. *In:* Electronics Goes Green 2008, Fraunhofer IRB Verlag Stuttgart Germany.
Wang, G., Fan, Z., Wu, D., Qin, L., Zhang, G., Gao, C., & Meng, Q. (2014). Anoxic/aerobic granular active carbon assisted MBR integrated with nanofiltration and reverse osmosis for advanced treatment of municipal landfill leachate. Desalination, 349; 136–144.
Wang, H., Lv, S., Li, F., Liu, Q., & Ke, S. (2010). Study on the changes of urinary 8-hydroxydeoxyguanosine levels and burden of heavy metal around e-waste dismantling site. Sci. Total Environ., 408; 6092–6099.
Wang, H., Ma, J.W., Fan, X.Y., & Luo, Q. (2007). Research progress on enhancement of in situ

remediation of heavy metal by electrokinitics. Ecol. Environ. Sci., 16(1); 223–227.
Wang, J., & Chen, C. (2009). Biosorbents for metals removal and their future. Biotechnol. Adv., 27(2); 195–226.
Wang, J.P., & Guo, X.K. (2006). Impact of electronic wastes recycling on environmental quality. Biomed. Environ. Sci., 19; 137–142.
Wang, Y., Hu, J., Lin, W., Wang, N., Li, C., Luo, P., Hashmi, M.Z., Wang, W., Su, X., & Chen, C. (2016). Health risk assessment of migrant workers' exposure to polychlorinated biphenyls in air and dust in an e-waste recycling area in China: indication for a new wealth gap in environmental rights. Environ. Int., 87; 33-41.
Wei, L., & Liu, Y. (2012). Present status of e-waste disposal and recycling in China. Procedia Environ. Sci., 16; 506–514.
Widmer, R., Oswald-Krapf, H., Sinha-Khetriwal, D., Schnellmann, M., & Boni, H. (2005). Global perspectives on e-waste. Enviro. Impact Assess. Rev., 25; 436–458.
Wong, C.S.C., Duzgoren-Aydin, N.S., Aydin, A., & Wong, M.H. (2007). Evidence of excessive releases of metals from primitive e-waste processing in Guiyu, China. Environ. Pollut., 148; 62–72.
Wu, G., Kang, H., Zhang, X., Shao, H., Chu, L., & Ruan, C. (2010). A critical review on the bio-removal of hazardous heavy metals from contaminated soils: issues, progress, eco-environmental concerns and opportunities. J. Hazard. Mater., 174; 1-8.
Wu, L., Luo, Y., Christie, P., & Wong, M. (2003). Effects of EDTA and low molecular weight organic acids on soil solution properties of a heavy metal polluted soil. Chemosphere, 50; 819-822.
Wuana, R.A., & Okieimen, F.E. (2011). Heavy metals in contaminated soils: a review of sources, chemistry, risks and best available strategies for remediation. ISRN Ecology, 2011: 1-20.
Xing, G.H., Chan, J.K.Y., Leung, A.O.W., Wu, S.C., & Wong, M.H. (2009). Environmental impact and human exposure to PCBs in Guiyu, an electronic waste recycling site in China. Environ. Int., 35; 76–82.
Xu, L., Ge, J., Huo, X., Zhang, Y., Lau, A.T.Y., & Xu, X. (2016). Differential proteomic expression of human placenta and fetal development following e-waste lead and cadmium exposure in utero. Sci. Total Environ., 550; 1163–70.
Xu, L., Huo, X., Zhang, Y., Li, W., Zhang, J., & Xu, X. (2015 a). Polybrominated diphenyl ethers in human placenta associated with neonatal physiological development at a typical e-waste recycling area in China. Environ. Pollut., 196; 414–22.
Xu, P., Lou, X., Ding, G., et al. (2014 a). Association of PCB, PBDE and PCDD/F body burdens with hormone levels for children in an e-waste dismantling area of Zhejiang Province, China. Sci. Total Environ., 499; 55–61.
Xu, P., Lou, X., Ding, G., et al. (2015 b). Effects of PCBs and PBDEs on thyroid hormone, lymphocyte proliferation, hematology and kidney injury markers in residents of an e-waste dismantling area in Zhejiang, China. Sci. Total Environ., 536; 215–222.
Xu, P., Zeng, G.M., Huang, D.L., Feng, C.L., Hu, S., Zhao, M.H., Lai, C., Wei, Z., Huang, C., & Xie, G.X. (2012). Use of iron oxide nanomaterials in wastewater treatment: a review. Sci Total Environ., 424; 1-10.
Xu, X., Liu, J., Huang, C., Lu, F., Chiung, Y.M., & Huo, X. (2015 c). Association of polycyclic aromatic hydrocarbons (PAHs) and lead co-exposure with child physical growth and development in an e-waste recycling town. Chemosphere, 139; 295–302.
Xu, X., Liu, J., Zeng, X., Lu, F., Chen, A., & Huo, X., (2014 b). Elevated serum polybrominated diphenyl ethers and alteration of thyroid hormones in children from Guiyu, China. PLoS One, 9; e113699.
Yang, H., Huo, X., Yekeen, T.A., Zheng, Q., Zheng, M., & Xu, X. (2013). Effects of lead and cadmium exposure from electronic waste on child physical growth. Environ. Sci. Pollut. Res. Int., 20; 4441–4447.
Yang, T., Huang, H.J. & Lai, F.Y. (2017). Pollution hazards of heavy metals in sewage sludge from four wastewater treatment plants in Nanchang, China. Trans. Nonferrous Met. Soc. China, 27(10); 2249-2259.
Yang, W., Song, W., Li, J., & Zhang, X. (2020). Bioleaching of heavy metals from wastewater sludge with the aim of land application. Chemosphere, 249; 126134.
Yang, Y., Lu, X.S., Li, D.L., & Yu, Y.J. (2013). Effects of environmental lead pollution on blood lead and sex hormone levels among occupationally exposed group in an e-waste dismantling area. Biomed. Environ. Sci., 26; 474–484.

Yao, Z., Li, J., Xie, H., & Yu, C. (2012). Review on remediation technologies of soil contaminated by heavy metals. Procedia Environ. Sci., 16; 722–729.

Yesil, H., & Tugtas, A.E. (2019). Removal of heavy metals from leaching effluents of sewage sludge via supported liquid membranes. Sci. Total Environ. 693; 133608.

Yogeshwaran, V., & Priya, A.K. (2019). Removal of heavy metals using nano particles – a review. Indian Journal of Environmental Protection, 39(1); 17-21.

Zeng, J., Li, J., Gou, M., Xia, Z.-Y., Sun, Z.Y., & Tang, Y.Q. (2019a) Effective strategy for improving sludge treatment rate and microbial mechanisms during chromium bioleaching of tannery sludge. Process Biochemistry, 83; 70-79.

Zeng, X., Mathews, J., & Li, J. (2018). Urban mining of e-waste is becoming more cost effective than virgin mining. Environ. Sci. Technol., 52(8); 4835-4841.

Zeng, X., Xu, X., Qin, Q., Ye, K., Wu, W., & Huo, X. (2019b). Heavy metal exposure has adverse effects on the growth and development of preschool children. Environ. Geochem. Health, 41; 309–321.

Zhang, C., Lai, C., Zeng, G.M., Huang, D.L., Yang, C.P., Wang, Y., Zhou, Y.Y., & Cheng, M. (2016). Efficacy of carbonaceous nanocomposites for sorbing ionizable antibiotic sulfamethazine from aqueous solution. Water Res., 95; 103-112.

Zhang, Y., Xu, X., & Chen, A., et al. (2018). Maternal urinary cadmium levels during pregnancy associated with risk of sex-dependent birth outcomes from an e-waste pollution site in China. Reprod. Toxicol., 75; 49–55.

Zhao, F.J, Lombi, E., & Mc Grath, S.P. (2003). Assessing the potential of Zn and Cd phytoremediation with the *Hyperaccumulator Thlaspi caerulescens*. Plant and Soil, 249(1); 37-43.

Zhao, G.F., Wang, Z.J., Dong, M.H., Rao, K.F., Luo, J.P., & Wang, D.H. (2008). PBBs, PBDEs, and PCBs levels in hair of residents around e-waste disassembly sites in Zhejiang Province, China, and their potential sources. Sci. Total Environ., 397; 46–57.

Zhao, G.F., Wang, Z.J., Zhou, H.D., Zhao, Q. (2009). Burdens of PBBs, PBDEs, and PCBs in tissues of the cancer patients in the e-waste disassembly sites in Zhejiang, China. Sci. Total Environ., 407(17); 4831–4837.

Zheng, J., He, C.T., Chen, S.J., et al. (2017a). Disruption of thyroid hormone (TH) levels and TH-regulated gene expression by polybrominated diphenyl ethers (PBDEs), polychlorinated biphenyls (PCBs), and hydroxylated PCBs in e-waste recycling workers. Environ. Int. 102; 138–144.

Zheng, M.Y., Li, X.H., Zhang, Y., Yang, Y.L., Wang, W.Y., & Tian, Y. (2017b). Partitioning of polybrominated biphenyl ethers from mother to fetus and potential health-related implications. Chemosphere, 170; 207–215.

Zhou, D.M., Hao, X.Z., Xue, Y., Cang, L., Wang, Y.J., & Chen, H.M. (2004). Advances in remediation technologies of contaminated soils. Ecol. Environ. Sci., 13(2); 234–242.

Zhou, G., Zhang, H., Yang, W., Wu, Z., Liu, W., & Yang, C. (2020). Bioleaching assisted foam fractionation for recovery of gold from the printed circuit boards of discarded cellphone. Waste Manage., 101; 200–209.