Phytoremediation for E-waste contaminated sites

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7.1 Introduction

Electronic waste (E-waste) is defined as any electrical or electronic appliance discarded at the end of its life cycle that has become a solid waste of global concern during the last decade (Gaidajis et al., 2010; Ni and Zeng, 2009). Such waste can be categorized into a wide variety of classes including household appliances, IT and telecommunication equipment, consumer equipment, lightning equipment, tools, toys and sports equipment, medical devices, monitoring and control instruments, and automatic dispensers (Balde et al., 2017; Lundgren, 2012). The reported global E-waste generation in 2016 was approximately 45 million metric tons, which is expected to have an annual growth rate of 3%–4% (Balde et al., 2017). E-waste accumulation has become more significant in developed countries as compared to developing countries due to higher disposal rates (Lundgren, 2012; Ni and Zeng, 2009). In contrast, fewer rates of disposing of E-waste are observed in economically less developed or developing countries owing to prevailing trade, reuse, and resell of such appliances (Lundgren, 2012).

7.1.1 E-waste: types, composition, and hazardous components

A myriad of sources can contribute to the electronic and electrical rejects that make up highly complex waste streams. Inorganic and organic pollutants in E-waste amounting to more than a thousand have been reported in the scientific literature (Gaidajis et al., 2010). Inorganic pollutants can be attributed to toxic metals, such as mercury in switches and relays, lithium in batteries, beryllium in contact material, and several rare earth elements, such as antimony in flame retardants, gallium and indium in silicon chips, and LCD monitors (Kiddee et al., 2013; Li et al., 2011; Martin and Griswold, 2009; Tsydenova and Bengtsson, 2011). In addition, polyvinyl chlorides (PVCs) in fibers, polychlorinated biphenyls (PCBs) in transformers and condensers, polycyclic aromatic hydrocarbons (PAHs) from computer casings and circuit boards, polychlorinated dibenzodioxins and dibenzofurans (PCDD/DFs) from dismantling E-waste, polybrominated diphenyl ethers (PBDEs) from flame retardants, and chlorofluorocarbons (CFCs) from dismantled refrigerators and air conditioners form the enumerate range of organic pollutants (Birnbaum et al., 2003; Gaidajis et al., 2010; Kim et al., 2013; Leung et al., 2006; Ni and Zeng, 2009; Robinson, 2009; Safe, 1993; Siddiqi et al., 2003; Wilkinson et al., 1999).

7.1.2 Major impacts on human health and environment

E-waste has been reported to cause severe impacts due to the inefficient waste management techniques used. Majority of solid wastes are disposed in landfills, and on most occasions, these landfills are either open dumps or poorly managed sites (Barba-Gutiérrez et al., 2008; Robinson, 2009). It has also been reported that many of the E-waste recycling site operations are primordial such as open burning, toner sweeping, circuit board recycling, acid stripping of chips, plastic fragmentation, and melting, which enable the easy escape of toxic substances to the environment (Ni and Zeng, 2009). The acts of dumping, dismantling, burning, and leaching yield in various toxic leachates, particulate matter, effluents, and fumes (Frenk et al., 2010). Moreover, the current legislation gap facilitates illegal transboundary movement of E-waste where a large quantity is exported to some Asian countries such as China, India, Pakistan, and in some African countries, such as Ghana and Nigeria, which are known as crude E-waste recycling hotspots (Chi et al., 2011; Lundgren, 2012).

In light of the aforementioned pollutants, the predicament created has presented many environmental and health-related complications. Bioaccumulation of toxic components in animal tissues and their presence in food chains have severely affected the normal functioning of natural ecosystems. Arable lands comprising livestock is found to have accumulated the undesired outputs of E-waste. Due to their slow metabolic rates inside the guts of animals, these chemicals continue to persist inside them (Lundgren, 2012). Humans exposed to these chemicals have shown undesirable side effects relating to the gastrointestinal tract, the respiratory system, and other organs (Nordbrand, 2009). Coughing, choking, breathing difficulties, eye irritations, skin diseases, convulsions, and even death are possible outcomes (Prakash et al., 2010; Yu et al., 2006). A detailed description of potential pollutants attributed to E-waste, their sources, and deleterious health effects are shown in Table 7.1.

Incorporation of apt remediation schemes for E-waste management has been understood to meet six major areas of the sustainable development goals (SDGs) out of the seventeen that exist. Controlling the release of hazardous chemicals from these waste into the environment ensures good health and wellbeing of the society. Achieving clean water and sanitation leads to the conservation of aquatic ecosystems, thereby attaining the goal of protection of life underwater. Sustainable cities and communities can be developed by entailing the 3 R (reduce, reuse, and recycle) procedures which fulfill the goal of responsible consumption and production alongside this. The goal of decent work and economic growth which is focused on the

Table 7.1 Sources and deleterious health effects of potential pollutants attributed to E-waste.

Compound	Applied in E-waste	Health effects	References
Antimony (Sb)	A melting agent in CRT glass, plastic computer housings, and a solder alloy in cabling	A carcinogen causes stomach pain, vomiting, diarrhea, and stomach ulcers through inhalation of high levels over a long time period	Kiddee et al. (2013) and Li et al. (2011)
Arsenic (As)	Gallium arsenide is used in light emitting diodes, semiconductors, and LEDs	Chronic effects that cause skin disease, lung liver, bladder cancers, and impaired nerve signaling	Kiddee et al. (2013); Li et al. (2011) and Martin and Griswold (2009)
Barium (Ba)	Sparkplugs, fluorescent lamps, CRT gutters in vacuum tubes, and an oxygen-removing agent	Causes brain swelling, muscle weakness, liver, heart, and spleen damage, and high blood pressure	Kiddee et al. (2013) and Martin and Griswold (2009)
Beryllium (Be)	Power supply boxes, motherboards, relays, finger clips, and silicon-controlled rectifiers	Exposure to beryllium, a carcinogen can lead to beryllicosis, lung cancer, and skin disease	Kiddee et al. (2013) and Li et al. (2011)
Cadmium (Cd)	Rechargeable Ni-Cd batteries, semiconductor chips, infrared detectors, metal coating, solder joints, UV stabilizers, and toners in photocopying	Causes kidney disease, lung damage, and fragile bones	Kiddee et al. (2013); Li et al. (2011) and Martin and Griswold (2009)
Chromium (Cr)	Plastic computer housing, cabling, hard disks, as a colorant in pigments, protective coatings on metal (electroplating), magnetic tapes, and floppy disks	Can cause DNA damage, permanent eye impairment, the lining of the nose, nose ulcers, runny nose, and breathing problems such as asthma, cough, wheezing, allergic reactions, liver and kidney damage as well as skin irritation	Kiddee et al. (2013); Li et al. (2011) and Martin and Griswold (2009)

(*Continued*)

Table 7.1 (Continued)

Compound	Applied in E-waste	Health effects	References
Lead (Pb)	Solder, lead-acid batteries, cathode ray tubes, cabling, printed circuit boards, fluorescent tubes, X-ray shielding devices, and stabilizers in PVC	Can damage the brain, nervous system, kidneys, reproductive system, and cause blood disorders. Has acute and chronic effects	Kiddee et al. (2013) and Martin and Griswold (2009)
Mercury (Hg)	Batteries, backlight bulbs or lamps, flat panel displays, switches, and thermostats	Can damage the brain, kidneys, and fetuses. Causes shyness, tremors, changes in vision or hearing, memory problems, lung damage, nausea, vomiting, diarrhea, increases in blood pressure or heart rate, skin rashes, and eye irritation	Kiddee et al. (2013); Li et al. (2011) and Martin and Griswold (2009)
Nickel (Ni)	Batteries, computer housing, cathode ray tubes, and printed circuit boards	Can cause an allergic reaction, bronchitis, reduced lung function, and lung cancers	Kiddee et al. (2013) and Li et al. (2011)
Selenium (Se)	Electronic semiconductors	High concentrations cause selenosis, neurological abnormalities, respiratory tract irritation, bronchitis, difficulty breathing, and stomach pains and coughing	Kiddee et al. (2013) and Martin and Griswold (2009)
Silver (Ag)	Electronic equipment, electrical contacts and conductors	Arygria, a blue-gray discoloration of the skin and other body tissues, breathing problems, lung and throat irritation, and stomach pains	Martin and Griswold (2009)
Polyvinyl chloride (PVC)	Monitors, keyboards, cabling, and plastic computer housing	Respiratory problems and an increased incidence of cancer	Kiddee et al. (2013) and Wilkinson et al. (1999)
Polychlorinated biphenyls (PCBs)	Condensers, transformers and heat transfer fluids, capacitor	Immunosuppression, liver damage, tumor promotion, neurotoxicity, damage to both male and female reproductive systems,	Kiddee et al. (2013) and Safe (1993)

	dielectrics, plasticizers, and printing inks	delayed cognitive development and behavioral problems elevated serum lipid levels, chloracne and related dermal lesions, possible hepatic damage, respiratory problems, cancer deaths, and lower birth weights	
Polycyclic aromatic hydrocarbons (PAHs)	Open burning of computer casings and circuit boards, rubber material of printer rollers	Has acute and chronic effects. Impaired lung function, asthmatic and thrombotic effects, increase risk of lung, skin, bladder, and gastrointestinal cancers	Kim et al. (2013) and Leung et al. (2006)
Polybrominated diphenyl ethers (PBDE)	Burnt plastic dump site and the printer roller	Impaired learning and memory functions, as well as interfering with the thyroid, disrupting normal estrogen pathways, live tumors, and gastrointestinal syndromes	Ni and Zeng (2009) and Siddiqi et al. (2003)
Polychlorinated dibenzo-p-dioxins and dibenzofurans (PCDDs/Fs) and polybrominated dibenzo-p-dioxins and dibenzofurans (PBDDs/Fs)	During the dismantling of E-waste	Lethality, wasting, thymic atrophy, tetratogenesis, reproductive effects, chloracne, immunotoxicity, enzyme induction, decrease in T4 and vitamin A, and increased hepatic porphyrins	Birnbaum et al. (2003) and Ni and Zeng (2009)

provision of a safe and reliable working environment where employees can innovate and conduct productive activities is also met (Balde et al., 2017).

As per the Global E-waste Monitor 2017, only 41 countries of the world were statistically updated about the problem posed by E-waste, and 20% of the total E-waste production was documented to be appropriately recycled. The remaining were either discarded into general waste streams or recycled under substandard conditions (Barba-Gutiérrez et al., 2008; Robinson, 2009). In the recent past, rapidly growing concerns about E-waste have gained much research interest worldwide to the extent that targets to minimize its volume by 50% by 2020 has been discussed at the International Telecommunication Union (ITU) (Balde et al., 2017). Therefore incorporation of proper management techniques for existing E-wastes and remediation practices for contaminated sites by E-wastes is vital.

7.2 Conventional management techniques for E-waste and associated release of pollutants

In order to manage the day to day generating E-waste loads, there are several management techniques in use. Recycling of E-wastes, thermal treatments methods, use of acid baths, and finally landfill disposal or disposal into dumpsites are main methods which are extensively utilized for E-waste management.

7.2.1 Recycling

Recycling involves dismantling and disassembly of different parts of obsolete electrical and electronic equipment together with their eventual reprocessing. Descriptively, recycling comprises with some subprocesses such as separation of the parts having hazardous substances (cathode ray tubes and printed circuit boards) and segregation of ferrous and nonferrous metals (Asante et al., 2012). With the use of an efficient E-waste recycler some precious metals including gold, copper, and lead can be recovered. Recycling can be undertaken either manually or mechanically where it facilitates to reutilize a wide range of electrical equipment such as mobile phones, laptops, keyboards, CPUs, monitors, cables, and connecting wires (Heacock et al., 2015).

However, vast quantities of E-wastes which are undergoing recycling processes leave significant environmental footprints on soil, water, and air worldwide (Table 7.2). Moreover, human health effects with often poisoning incidents are in greater consideration. Many local people who are engaged with the recycling activities are reported to be suffered from physical injuries, neurological disorders, reproductive problems, respiratory diseases, and cancers (Huang et al., 2011). The issues are extensively accounted in some regions such as Guiyu and Taizhou in China, Gauteng in South Africa, New Delhi in India, and Accra in Ghana, where large E-waste recycling sites are located (Tsydenova and Bengtsson, 2011).

Table 7.2 Pollutants released from the recycling of E-waste.

Pollution category	Country/region	Pollutants	Recycling process	References
Soil	Guiyu, China	POPs and trace metals (Pb, Cd, Ni, Cr, Hg and As) Organic pollutants PAHs, PCBs, brominated flame retardants (BFRs)	Crude thermal processes	Chen et al. (2009); Herat and Agamuthu (2012) and Wang et al. (2011)
	Guiyu and Taizhou, China	PBDEs, PAHs, PCDD/Fs and PCBs	Uncontrolled dismantling and acid treatment	Huang et al. (2011) and Tang et al. (2010)
	Bangalore, India	Ag, Bi, Cd, Cu, In, Hg, Pb, Sn and Zn	—	Ha et al. (2009) and Möller et al. (2012)
Air	Guiyu, China	Polybrominated dibenzo-p- dioxin/furans (PBDD/Fs)	Production, weathering, and recycling of flame-retardant plastics	Ni et al. (2010) and Sepúlveda et al. (2010)
		Chlorinated and brominated compounds, PBDEs and trace metals (Cr, Zn and Cu)	—	
	Bangalore, India	Bi, Co, Cr, Cu, In, Mn, Pb, Sb, Sn, and Tl	—	Ha et al. (2009)
	Thailand	Dust containing compounds (e.g., BFRs, TPP, phthalates, and Cd).	Shredding	Muenhor et al. (2010)
		PPBDEs	E-waste storage facility	Muenhor et al. (2010)
Water	Liangjian and Nanya rivers, China	Dissolved metal, higher concentrations of Pb	—	Sepúlveda et al. (2010)

7.2.2 Dumps and landfills

Sanitary landfills are considered as the most common E-waste disposal technique which aims to reduce or mitigate the potential risks associated with the environment and human health. Landfills are typically positioned in areas where prevailing land features can perform as natural buffers between the environment and landfills. Trenches are made in excavated soil and impervious liners are formed prior to burying E-waste in order to prevent escaping the hazardous materials (Li et al., 2009).

Further, controlled dumps are used as an alternative method for sanitary landfills. They show some similarities to sanitary landfills where pollutants are dumped in mixtures. While having the well-planned capacity, these dumps do not associate with cell-planning. The pollution incidents may become complicated and diversified due to the mixed nature of pollutants and the absence of any gas management and proper covering (Kiddee et al., 2013).

However, due to the potential leaching of toxic substances into the soil and groundwater, landfills and dumps are not environmentally sound processes. It has been proved that E-waste receiving dumps and landfills are a major cause of groundwater contamination (Kasassi et al., 2008). The leachates which percolate from E-waste sites are reported to contain significantly higher concentrations of trace metals along with dissolved and suspended organic and inorganic substances (Spalvins et al., 2008). Those pollutants can be transferred along the food chains and may be accumulated in the living bodies finally affecting human health. Although the health and environmental risks are comparatively low in sanitary landfills, the initial cost is comparatively higher (Li et al., 2009).

7.2.3 Thermal treatment

Thermal treatment involves the application of heat to treat and decompose waste materials through different approaches (Sivaramanan, 2013). Open Burning is the primary method of thermal waste treatment but is considered as an environmentally invasive process. No pollution controlling devices are engaged in open burning, allowing pollutants to escape into the environment. This method is practiced in most of the countries since it provides a cheaper solution for solid waste treatment (Singh and Gautam, 2014).

Incineration is considered as one of the most common methods where E-waste undergoes combustion at high temperatures. Specifically designed incinerators are used for the controlled combustion in the presence of oxygen (Gramatyka et al., 2007). This is one of the most commonly used methods of E-waste management in China, Africa, Pakistan, and India. This process is demonstrated to be advantageous as the means of heat and energy recovery. Additionally, a significant reduction in waste volume can be achieved through the process. Nevertheless, incineration plants are considered as a source for a series of extremely toxic pollutants with neurotoxins and carcinogens (Vats and Singh, 2014).

Gasification and pyrolysis are more or less similar methods, where the waste materials are allowed to decompose under low oxygen levels and very high temperatures. Pyrolysis is undertaken in the absence of oxygen to convert the wastes into fumes, oils, and charcoal while gasification allows a considerably low amount of oxygen in the process. The emissions are low in comparison to the other thermal treatment methods (Sivaramanan, 2013).

Generally, thermal treatment generates substances which are more likely to be toxic in comparison to their ordinary forms. Noxious fumes are emitted during the processes including dioxins, furans, and harmful gases such as mercury and cadmium (Lukose, 2015). Erotic fumes are released with the heating of plastic or PVC circuit boards. The fumes may contain well-known carcinogens such as polychlorinated dibenzo-para-dioxins (PCDDs), polycyclic aromatics (PCAs), and polychlorinated dibenzofurans (PCDFs) along with other toxic gases such as carbon monoxide, sulfur dioxide, and nitrogen oxides (Zheng et al., 2008). Lower levels of trace metal residues also can be contained in these fumes.

7.2.4 Acid bath

Mostly in acid bath technique, electronic circuit boards are submerged in sulfuric, hydrochloric, or nitric acid solutions and soaked for a determined time period in order to extract some valuable metals (Sivaramanan, 2013). Copper, silver, and gold are some extractable metals which get dissolved in the concentrated acid solution during the soaking period and subsequently precipitated. Precipitated metals are recovered and utilized in manufacturing other products while acid wastes are discharged into the environment. These hazardous acid wastes and chemicals find their way to water sources as they end up with groundwater. For instance, Yamuna river banks in India are reported as a well-known site for acid baths. Moreover, this method can pose a health risk for humans due to exposure to acidic fumes, which are containing hazardous compounds (Sivakumaran et al., 2017).

All the methods discussed above have their own drawbacks and are involved in releasing contaminants into the environment. E-waste recycling sites bears significance since they release toxic metals and organic contaminants to the surrounding areas. The final product of thermal treatment techniques such as incineration generate bottom ash rich in toxic metals. Moreover, open dumping sites and poorly managed landfills cause to release contaminants rich landfill leachates which can pollute groundwater system and surrounding soils.

Hence, innovative, environment-friendly, and low-cost remediation techniques have to be investigated to remediate contaminated areas by E-waste. Fig. 7.1 listed widely used physicochemical and biological approaches for remediation of contaminants, which are resulted from E-waste. However, green approaches to mitigate environmental risk have become viable choices.

Bioremediation is an approach which utilizes natural biological activities to destroy or remove harmful contaminants from the environment. This approach relies on cost-effective and low-tech methods having high public acceptance to deliver on-site remediation of contaminants. Bioremediation uses a wide variety of

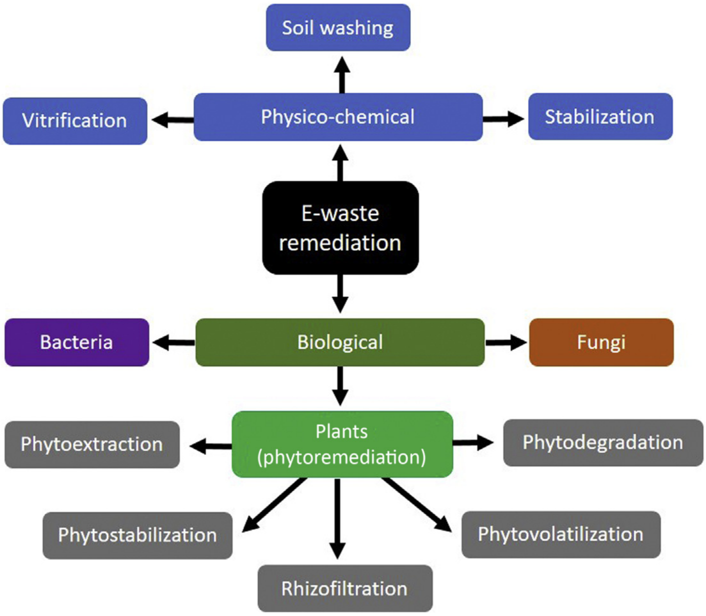

Figure 7.1 Available techniques to remediate contaminants from E-wastes.

bacteria, fungi, and plant species which are evolved to remove or destroy specific contaminant or range of contaminants through their specialized metabolic pathways. Many studies investigated the capacity of bioremediation for remediation of possible pollutants from E-wastes (Hiremath et al., 2015; Jiang et al., 2018; Kang et al., 2016). The term "phytoremediation" is particularly adopted for the situations which use plant species as a bioremediation agent.

7.3 Phytoremediation to mitigate contaminant from E-waste

The ability of plants, wild or genetically modified, to be used in the decontamination of the environment, termed phytoremediation, has been in progress ever since the 1990s. Research interest in this regard has led to consider phytoremediation as an appropriate means of E-waste remediation (Alkorta and Garbisu, 2001; Campos et al., 2008; Lukose, 2015).

A research gap is created because the knowledge on phytoremediation was scattered, and it has been the effort of the authors to amalgamate these details in order to fill this gap. Therefore hereafter this chapter focuses on the fundamentals of phytoremediation, phytoremediation approaches for inorganic, and organic contaminants in E-waste along with its associated advantages and limitations.

7.3.1 A brief history on the use phytoremediation

Phytoremediation is a plant-based bioremediation technology used to remediate trace metals, hazardous inorganic and organic contaminants from soils, sediments, surface and groundwater, wastewater, and the atmosphere (Luo et al., 2015; Susarla et al., 2002). The generic term of phytoremediation originates from the Greek prefix "phyto," which stands for "plant," and the Latin suffix "remedium," which means "able to cure" or "restore" (Laghlimi et al., 2015). This conception was introduced by Chaney (1983) to remediate metal-polluted sites using "hyperaccumulators," that is, the plants considered more efficient in the phytoremediation processes. Brooks et al. (1977) discovered hyperaccumulators as plants which could accumulate nickel in the shoot tissue at a concentration of 1000 mg/kg of the plant biomass which accounts >0.1%−1% of the dry weight of the plant. Around 500 species of plants under about 101 families have been discovered as hyperaccumulators, having the potential to thrive and accumulate high concentration of contaminants (Ghosh and Singh, 2005; Mahar et al., 2016; Prasad and De Oliveira Freitas, 2003; Sarma, 2011).

7.3.2 Mechanisms in phytoremediation

Plants utilized for phytoremediation possess specialized physiological characteristics compared with other plants. The number of mechanisms evolved in these plants, namely; phytoextraction, phytostabilisation, rhizofiltration, phytovolatilization, and phytodegradation/phytotransformation are mainly involved in the pollutant removal through phytoremediation. Fig. 7.2 explains the above-mentioned phytoremediation mechanisms in a simple manner.

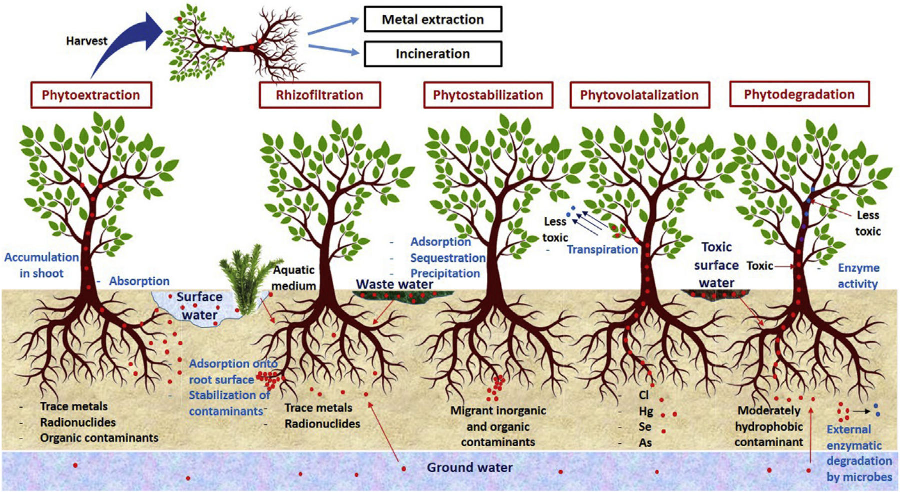

Figure 7.2 Mechanisms involved in contaminant mitigation by phytoremediation.

7.3.2.1 Phytoextraction

Phytoextraction is the removal of contaminants from soil, surface water, or groundwater through absorbing contaminants by plant roots and translocating them to above-ground tissues of the plant facilitating accumulation in the shoot biomass (Mahar et al., 2016; Susarla et al., 2002). This mechanism is adopted by hyperaccumulators to concentrate trace metals, radionuclides, and organic compounds in their biomass which is harvested later on and finally disposed through burning or recovered through metal extraction (Lee, 2013; Tangahu et al., 2011). Phytoextraction is possible for remediation of low to moderate levels of contaminations in the superficial layers of the soil as many hyperaccumulators cannot sustain in high contaminant loads (Prasad and De Oliveira Freitas, 2003).

7.3.2.2 Phytostabilization

This is the use of plants to stabilize or immobilize migrant inorganic and organic contaminants in the soil and water through roots or the rhizosphere thereby either reducing or preventing leaching of pollutants to groundwater and reducing the bioavailability of the pollutants in the environment (Cristaldi et al., 2017; Lee, 2013; Tangahu et al., 2011). Phytostabilization does not degrade nor necessarily remove contaminants from the soil but focuses mainly on stabilizing pollutants in the soil around the root system (Gerhardt et al., 2017). The mechanism may involve adsorption onto the root surface, sequestration within root tissues, and precipitation or complexation of metals with organic compounds in the root zone (Mahar et al., 2016).

7.3.2.3 Rhizofiltration

Rhizofilteration utilizes terrestrial or aquatic plants for the removal of organic and inorganic metal contaminants from surface water, groundwater, and wastewater by adsorption, precipitation pollutants onto the plant roots or accumulation pollutants in the root tissues in the surrounding solution of the root zone (Cristaldi et al., 2017; Ghosh and Singh, 2005; Lee, 2013). This method is usually practiced for the removal of trace metal and radio nuclei (U-Uranium) in aquatic environments and treatment of industrial discharges by means of a constructed wetland. Plants are grown hydroponically and then later on transplanted in the real aquatic environment of metal contaminations. This process is effective for remediation of low concentration of pollutants in large water bodies (Salt et al., 1995).

7.3.2.4 Phytovolatilization

Phytovolatilization requires the volatilization of contaminants taken up by the plants. Once contaminants are absorbed at the root level, they are being transported through the vascular tissues to the foliage where the contaminants are transformed into their less toxic gaseous forms as a result of metabolic processes and subsequently released to the atmosphere via transpiration (Cristaldi et al., 2017; Laghlimi et al., 2015;

Sharma and Pandey, 2014). Phytovolatilization is utilized for the removal of chlorinated organic compounds such as tetrachloroethane and trichloromethane, volatile trace metals like Hg, Se, and As from the soil and water (Lee, 2013; Susarla et al., 2002). Mostly this technique is used to treat Hg to form less toxic mercuric compounds that eventually end up into the air. The major drawback of phytovolatilization is that the contaminants are not entirely fixed instead they can recycle by resettling on the land and water through precipitation (Mahar et al., 2016; Sharma and Pandey, 2014).

7.3.2.5 Phytodegradation/phytotransformation

Phytodegradation is either the external enzymatic degradation of contaminants in the rhizosphere or the breakdown/transformation of contaminants taken up by the plants to less toxic compounds through metabolic modification within the plant (Pandey and Bajpai, 2019; Tangahu et al., 2011). Plants produce a wide range of enzymes: dehalogenases, peroxidases, reductases, and oxygenases which capable of transforming contaminants to nontoxic products inside the plant as well as in the rhizosphere with the aid of the microbial community (Ghosh and Singh, 2005). Phytodegradation applies for moderately hydrophobic organic chemicals including herbicides, insecticides, pesticides, chlorinated solvents, and inorganic contaminants for the recovery of contaminated surface and groundwater and even soil at low concentrations (Ghosh and Singh, 2005; Lee, 2013).

7.3.3 Phytoremediation approaches for different contaminants from E-wastes

Out of various remediation techniques utilized so far to remediate E-waste contaminants, phytoremediation has been identified as a promising tool in terms of eco-conservation and cost-benefit analysis. Ever since government organizations and academic institutions have been working on the removal of these contaminants in the laboratory and field trial scale, developing them further into effective full-scale field application.

Recently, most of the phytoremediation approaches have been applied to the E-waste contaminated sites in the Chinese region. Globally, the highest amount of E-waste generated in China about 7.2 million tons, which is expected to grow up to 27 million tons by the year 2030 (Balde et al., 2017). The city of Guiyu in Guangdong Province of China is known to be the largest electronic waste recycling site in the world while Taizhou region of the Zhejiang province is also a well-known E-waste processing center (Meagher, 2000; Robinson, 2009). The soil in these areas are vastly contaminated with trace metals, including lead, cadmium, copper, and organic pollutants, such as PCBs, PBDEs, and phthalic acid esters (PAEs) leached out from the electronic waste (Chen et al., 2010; Huang et al., 2011; Luo et al., 2017; Shen et al., 2009).

Although phytoremediation is a favorable technique for contaminant eradication, the conventional methods are however, time-consuming and less effective to be applied in the real-life scenario. In addition, due to the binding tendency of hydrophobic organic contaminants to soil organic matter, the bioavailability of contaminants in the soil becomes very low, restricting the extraction, removal, and degradation by plants themselves (Tu et al., 2011). Incorporation of various cutting-edge techniques including, gene modification (Da Conceição Gomes et al., 2016), chelator application (De Araújo and Do Nascimento, 2010; Luo et al., 2016), surfactant application (Chen et al., 2010), electrokinetic assistance (Cang et al., 2012; Lim et al., 2012), soil microbial enhancement (Teng et al., 2010), and microbial enzyme stimulation (Tu et al., 2011) could enhance the overall removal efficiency and the bioavailability during phytoremediation.

The studies of Shen et al. (2009) and Chen et al. (2010) have employed randomly methylated and nonmethylated β-cyclodextrin, a surfactant, to demonstrate the potential removal of PCBs with several plant species in the presence and absence of rhizosphere. The higher levels of PCB removal related to the amendment with surfactant and soil microbial activity as surfactants are capable of increasing the water solubility of the organic contaminants making them available for the plant extraction (Liu et al., 2013). The effect of chelating agents such as citric acid, nitrilotriacetic acid, and EDTA was examined by De Araújo and Do Nascimento (2010) for phytoremediation of lead. A multitechnique phytoremediation study was done by Luo et al. (2017) to test the effect of AC and DC electric fields ranging from 2 to 10 V simultaneously with foliar cytokinin and EDTA treatment to remediate cadmium, copper, and lead through *Eucalyptus globulus*. This combined approach was proved to be efficient than individual methods suggesting the fact that the integration of other techniques with phytoremediation can be successfully applied to eliminate contaminants from E-waste sites. Table 7.3 indicates the detailed information about plant species which were used for removal of different kind of contaminants from E-wastes and percentage contaminant removal or bioaccumulation resulted through phytoremediation process.

7.3.4 Advancement of phytoremediation for remediation of E-waste contaminated sites

Despite the use of traditional plant varieties for phytoremediation, there are several other methods that have been evolved as an effective strategy of remediation. Incorporation of mycorrhizal fungi and/or other soil organisms, use of invasive plants and transgenic plants might be the promising advances of phytoremediation for E-waste contaminated sites.

7.3.4.1 Use of mycorrhizal fungi and other soil organisms

Mycorrhizal fungi show extensively evolved, mutualistic relationship with plant roots of widespread plant families. These fungal interactions provide numbers of benefits for plants, including the supply of mineral nutrients, which ultimately involve for better survival and high biomass production of plants (Mafaziya and Madawala, 2015). Not only these interactions enable plant species to live in

Table 7.3 Phytoremediation approaches for E-waste contaminated sites in different places in the world.

Contaminated site or source	Plant species	Amendment	Contaminant	Contaminant removal or bioaccumulation (% or µg/g)		References
Taizhou city, China		Randomly methylated-β-cyclodextrins (RAMEB) (3.0%)	Polychlorinated biphenyls (PCBs)	Nonamended soil[a]	amended soil[a]	Shen et al. (2009)
	Rice (*Oryza sativa*)			26.9%	34.4%	
	Alfalfa (*Medicago sativa L.*)			26.6%	34.6%	
	Ryegrass (*Lolium perenne L.*)			28.5 %	31.4%	
	Tall fescue (*Festuca arundinacea*)			25.6 %	48.1%	
Taizhou city, China		β-cyclodextrin (3.0%)	PCB	Nonamended soil[a]	amended soil[a]	Chen et al. (2010)
	Rice (*Oryza sativa*)			26.9%	23.8%	
	Alfalfa (*Medicago sativa L.*)			26.6%	18.3%	
	Ryegrass (*Lolium perenne L*)			28.5%	31.7%	
	Tall fescue (*Festuca arundinacea*)			25.6%	27.3%	

(*Continued*)

Table 7.3 (Continued)

Contaminated site or source	Plant species	Amendment	Contaminant	Contaminant removal or bioaccumulation (% or μg/g)		References
Taizhou, Zhejiang Province, China	Alfalfa *(Medicago sativa L.)*	–	PCB	Soil[a] 31.4 % (first year) 78.4 % (second year)		Tu et al. (2011)
Yaocuowei, Guangdong Province, China	Italian ryegrass (*Lolium multiflorum L.*) Pumpkin *(Cucurbita pepo spp.*) Maize *(Zea mays L.)*	–	Polybrominated diphenyl ethers (PBDEs)	Soil[a] 13.3%–21.7%		Huang et al. (2011)
Taizhou, Zhejiang Province, China	Alfalfa *(Medicago sativa L.)*			Root[b]	Shoot[b]	Teng et al. (2010)
		Uninoculated alfalfa	PCB	27.4	230.8	
		Alfalfa + *G. caledonium*		36.6	324.5	
		Alfalfa + *R. meliloti*		42.1	326.1	
		Alfalfa + *G. caledonium* + *R. meliloti*		46.9	267.8	
Automobile-battery recycling facility, Brazil	*Maize (Zea mays)*		Pb	Root[b]	Shoot[b]	De Araújo and Do Nascimento (2010)
		Citric acid (30 mM)		15,604	1545	
		Nitrilotriacetic acid (10 mM)		6892	836	
		EDTA (10 mM)		52,151	5787	

Taizhou, Zhejiang Province, China	Alfalfa *(Medicago sativa L.)*	Intercropping	Phthalic acid esters (PAEs)	Shoot[b] 3.36		Ma et al. (2013)
	Ryegrass *(Lolium perenne L.)*			3.10		
	Tall fescue (*Festuca arundinacea*)			3.05		
Landfill leachate, Kenya	Water hyacinth (*Eichhornia crassipes*)	—	PCBs	Roots[b] 0.179		Omondi et al. (2015)
Guiyu, Guangdong Province, China	*Eucalyptus globulus*			Root[b]	Shoot[b]	Luo et al. (2017)
		Nonamended	Cd	0.81	0.23	
			Pb	40.2	7.92	
			Cu	50.13	28.31	
		EDTA (0.5 mM)	Cd	3.16	2.68	
			Pb	128.5	56.6	
			Cu	89.2	56.8	
		Electric field (2 V DC)	Cd	1.32	0.42	
			Pb	47.2	9.67	
			Cu	56.8	32.9	
		Electric field (4 V DC)	Cd	1.89	0.58	
			Pb	62.8	11.96	
			Cu	62.5	38.7	
		Electric field (10 V DC)	Cd	2.05	0.62	
			Pb	63.8	10.62	
			Cu	68.2	39.1	
		Cytokinin (20 mg kg^{-1})	Cd	1.55	2.93	
			Pb	46.3	23.1	
			Cu	59.8	35.3	

(*Continued*)

Table 7.3 (Continued)

Contaminated site or source	Plant species	Amendment	Contaminant	Contaminant removal or bioaccumulation (% or µg/g)		References
Guiyu, Guangdong Province, China	*Eucalyptus globulus*			Root[b]	Shoot[b]	Luo et al. (2018)
		Nonamended	Cd	0.63	0.23	
			Pb	32.80	5.80	
			Cu	60.2	33.3	
		Electric field (2 V DC)	Cd	0.89	0.29	
			Pb	40.3	8.6	
			Cu	69.8	35.9	
		Electric field (4 V DC)	Cd	1.07	0.35	
			Pb	55.2	9.3	
			Cu	73.5	38.2	
		Electric field (10 V DC)	Cd	1.31	0.41	
			Pb	62.8	12.5	
			Cu	75.1	41.6	
		Electric field (2 V AC)	Cd	0.72	0.52	
			Pb	35.1	20.6	
			Cu	64.2	59.8	
		Electric field (4 V AC)	Cd	0.93	0.68	
			Pb	42.9	29.8	
			Cu	68.1	63.7	
		Electric field (10 V AC)	Cu	1.12	1.03	
			Pb	55.6	32.5	
			Cu	70.3	71.2	

[a] Contaminant removal %.
[b] Bioaccumulation in the plant shoot/root.

nutrient-poor and contaminated soils but also assist them to uptake and detoxification of a range of pollutants, making them possible agents for effective phytoremediation (Bahraminia et al., 2016).

Bahraminia et al. (2016) examined the effect of two mycorrhizal fungal species with Vetiver grass (*Vetiveria zizanoides*) on phytoremediation of lead-contaminated soils. Inoculation of two mycorrhizal species, *Glomus versiforme*, and *Rhizophagus intraradices* has been involved for the significant increase in uptake efficiencies, phytoextraction, and translocation factor of lead, which is one of the major contaminants in E-waste. The study of Abu-Muriefah (2016) highlighted the use of *Glomus deserticola* to enhance phytoremediation capabilities of *Eucalyptus rostrata* toward the rehabilitation of trace metal contaminated sites. Moreover, Schneider et al. (2016) revealed the positive correlation exhibited on plant distribution with arbuscular mycorrhizal root colonization in lead-contaminated sites. This study explains the effect of the mycorrhizal associations on the survival of plant communities in harsh environmental conditions, which further influence phytoremediation mechanisms such as phytostabilization. Furthermore, the study of Ren et al. (2017) examined the effect of triple symbiosis among legume species (*Sesbania cannabina*), arbuscular mycorrhizal fungi (*Glomus mosseae*) and rhizobia (*Ensifer* sp.) for phytoremediation of PAHs, one of the possible contaminant classes resulting from E-wastes. The interaction of plant, arbuscular mycorrhizal fungi, and rhizobial bacteria resulted the highest reduction of PAHs, phenanthrene and pyrene by >97% and 85%−87%, respectively. This study suggests the synergistic effect evolves from arbuscular mycorrhizal and rhizobium bacteria which improve phytoremediation capabilities of plants by increasing the biomass production and PAHs accumulation inside the plant tissues.

Other than mycorrhizal associations, actions of soil biota also have a major influence on the increase or decrease of phytoremediation efficiency. Luo et al. (2016) studied about the involvement of nitrogen fixers such as chickpeas (*Cicer arietinum*) and earthworms for the biomass production and phytoremediation efficiency of *Eucalyptus globulus* for Cd, a major contaminant released from E-wastes. That study indicated that the *Eucalyptus globulus* with earthworm required 30% less time for complete removal of Cd from the system than the second most successful system. On the other hand, soil borne pathogens and denitrifying bacteria involved in causing plant diseases and limiting soil nutrients could have negative impacts on phytoremediation.

Therefore the proper understanding of mycorrhizal associations of plants which are used in phytoremediation is an urgent need to increase the efficiency and effectiveness of contaminant removal from the lands contaminated with E-wastes. Further, the knowledge about other kinds of symbiotic relationships such as rhizobial bacteria and the contribution of other soil macroorganisms which increase the survival, growth rate, and biomass production of phytoremediation agents is essential to harvest maximum advantage of phytoremediation.

7.3.4.2 The capacity of invasive plants for phytoremediation

Invasive plants have a unique set of characteristics including high growth rates, tolerance to harsh environmental conditions, high reproductive rate, and adaptive abilities for a vast range of environmental conditions. These characters could be useful when the use of them as agents for phytoremediation of E-wastes contaminated sites. Several studies investigated the potential of invasive or potentially invasive plants on the phytoremediation process.

The study of Chinmayee et al. (2012) identified *Amaranthus spinosus*, a potentially invasive species as a potential phytoremediation agent for trace metal contaminated sites. This study emphasized the ability of examined plant species for effective bioaccumulation and translocation of cadmium, copper, and zinc. Similarly, Wei et al. (2018) studied about phytoremediation abilities of three invasive species in China, namely, *Chromolaena odorata*, *Bidens pilosa*, and *Praxelis clematidea*, for removal of cadmium. The results of this study revealed that all the three tested plant species had the tolerance to grow in cadmium contaminated soils, and *Chromolaena odorata* expressed high bioaccumulation capacity for cadmium than others. Also, Pandey (2012) recognized *Ipomoea carnea* as an agent for phytoremediation as it possesses favorable characteristics including easy propagation through vegetative methods, high level of tolerance to, flooding, desiccation, salinity, pH, and toxic metals.

Moreover, its capacity to grow in nutrient poor conditions, high growth rate, and unpalatable nature correspondingly make it an effective phytoremediation agent.

Furthermore, Ekperusi et al. (2019) described the phytoremediation application of aquatic macrophyte, Duckweed (*Lemna minor*). Duckweed has extensive phytoremediation capabilities for a wide range of contaminants, including trace metals, organic pollutants, dyes, and radioactive wastes. Therefore it has high potential to apply for wastewater systems contaminated with multiple components of E-wastes.

However, the use of invasive plants as phytoremediation agents might induce ecological and human health-related consequences, if they manage to escape into natural habitats. Invasive plant species have abilities to adapt to a wide range of environmental conditions, and their high reproduction rates allow them to spread in the natural environment over the native plant species. Therefore utilizing them for phytoremediation purposes should be done under extreme caution with regular monitoring.

7.3.4.3 Transgenic plant technology as phytoremediation approach

A limited number of plant species had been identified as hyperaccumulators, and developing of new plant varieties for remediation of emerging contaminants by conventional breeding techniques is a challenge (Gunarathne et al., 2019). Survival of plant species is highly dependent on the edaphic conditions and environmental factors which vary among different regions of the world. Moreover, intrinsic factors such as less biomass production, slow growth rate, and less adaptability that might be associated with hyperaccumulators limit their usability as "real life" phytoremediation agents in field conditions. In this regard, transgenic plants with enhanced remediation capabilities have been introduced to overcome the limitations and drawbacks that are associated with traditional plant varieties used for phytoremediation (Ellis et al., 2004).

Transgenic plants are the plants which have been genetically modified utilizing recombinant DNA technology to express exogenous genes or modify endogenous genes (Key et al., 2008). Exogenous genes, including peroxidases and monooxygenases introduced into the plant genome have a great capacity for detoxification and remediation of contaminants (Wang et al., 2015). The first major attempts in transgenic plant technology for phytoremediation have been made to produce trace metal tolerance plants (Van Aken, 2008). However, several studies were conducted during the past few decades to produce viable transgenes for effective remediation of a wide range of contaminants. Details of some of the recent studies are stated below.

The study of Zhang and Liu (2011) involved to produce transgenic alfalfa, *Medicago sativa* by incorporating of human P450 2E1 (CYP2E1) and glutathione S-transferase (GST) genes through *Agrobacterium tumefaciens* mediated gene transfer method for remediation of mercury and trichloroethylene (TCE). Coexpressing of these two genes caused by synergistically improved tolerance and accumulation of heavy metals and organic complex contaminants. The transgene expressed a high tolerance for cadmium-TCE complexes than nontransgenes. A similar study has been conducted by Zhang et al. (2013) using the same transgenic alfalfa for removal of mercury-TCE complexes. Experimental results revealed that the improved plants which express these two genes are extensively tolerable for mercury-TCE complex pollutants. Further, those modified plants were able to accumulate many folds of mercury-TCE than nonmodified plants. Therefore modified alfalfa by human CYP2E1 and GST has high phytoremediation potential on soils contaminated with trace metals-organic complexes. Shim et al. (2013) also sued *Agrobacterium tumefaciens* mediated technique to establish yeast cadmium factor 1 (*ScYCF1*) gene in poplar (*Populus alba* X P. *tremula var. glandulosa*, BH1). The transgenes expressing *ScYCF1* were able to bioaccumulate higher amounts of trace metals, Cd, Zn, and Pb in root tissues. Further, these transgenic poplars showed extensive growth rates, less toxicity symptoms, and high content of Cd accumulation in shoots than nontransgenes. Moreover, Nahar et al. (2017) investigated the ability of tobacco (*Nicotiana tabacum*, var. Sumsun) incorporated with arsenic reductase 2 (*AtACR2*) gene from *Arabidopsis thaliana* for arsenic removal. The transgenic tobacco plants observed to be more resistant for arsenic and accumulated significantly higher arsenic concentrations in root systems than the nontransgenic wild variety. Therefore transgenic plant technology seems to be the most viable approach to develop new plants varieties for phytoremediation of E-waste contaminated sites.

However, the possible risks associated with these modified plants on environmental aspects is still a doubt. The transgenic technology involved to develop transgenes that have extreme capabilities to establish and thrive under harsh environmental conditions which present in polluted sites in order to facilitate phytoremediation in a more effective manner (Gunarathne et al., 2019). Therefore these transgenes bear the high potential to act like invasive species in the natural environment and can induce threats for the survival of native plant species (Ellstrand and

Schierenbeck, 2006). Moreover, the hybridization of native plant varieties with pollen from transgenic plants might lead for the extinction of native plant varieties by expression of deleterious genes such as gene which induce male sterility (Ellstrand and Schierenbeck, 2006). Therefore the development of new plant varieties for phytoremediation applications through transgenic plant technology should be done under extensive caution.

7.3.5 Advantages and limitations associated with phytoremediation for E-waste contaminated sites

Traditional soil remediation techniques are associated with several negative impacts on the environment including changes in edaphic conditions, generation of toxic byproducts, accelerated soil erosion, and economic nonviability (Luo et al., 2016). On the other hand, phytoremediation has been accepted by the public community as an environment-friendly approach for decontamination of polluted sites. Moreover, the use of phytoremediation saves about 60%−80% of the cost associated with traditional physicochemical remediation methods (Mwegoha, 2008). Phytoremediation is capable of mitigating most of the contaminants generated from E-wastes without interfering the natural soil functions. This technique not only removes the pollutants from contaminated sites but also reduces the leaching of trace elements, decreasing water percolation through the soil profile (Kidd et al., 2009). Further, the phytoremediation delivers added benefits such as carbon sequestration, soil erosion control, fuelwood production, biodiversity protection, and aesthetic value addition to the landscape, in addition to the contaminant mitigation (Hu et al., 2012; Pandey et al., 2015). Moreover, it is well suited over traditional methods for remediation of lands having a large area and a moderate amount of contamination.

Although phytoremediation has many advantages on contaminant mitigation, several associated disadvantages and drawbacks cannot be neglected. Even though that technique removes contaminants from the soil system, risk to transport them through food chains and bioaccumulate in tissues of organisms bears great significance from an environmental health perspective. (Rathod et al., 2014). The soil in E-waste contaminated sites generally comprise high concentrations of trace metals, so the risk to bioaccumulate them through food chains is high. Especially in cases which use plant species having edible fruits might create threats for human health. In particular, trace metals cannot be destroyed by biological pathways, but transformation between different oxidation status or complexation happen inside the plant body (Garbisu and Alkorta, 2001). Therefore the main drawback of this technique is to find proper disposal method for “pollutant-rich plants” that are used for uptake and storage of pollutants from contaminated sites (Pandey et al., 2015).

7.4 Remarks

Phytoremediation is not a new technique which is utilized for contaminant mitigation from the affected sites. However, it has been proven its effectiveness against remediation of emerging contaminants resulting from E-wastes. Due to the complex pattern of electronic product consumption by a modern human, generating E-waste load and the extent of the affected area are drastically increasing throughout the world. Therefore as an environment-friendly and cost-effective approach, phytoremediation is still receiving the attention of the scientific community for remediation of E-waste contaminated sites. This technique provides not only remediation but also offers added benefits, including erosion control, protection of biodiversity by providing habitats for animals and birds, and an increase in the scenic beauty of the environment. On the other hand, the public community also has positive attitudes toward phytoremediation.

Therefore new researches are emerging in the field of phytoremediation in order to increase the removal efficacy of contaminants, including emerging contaminants, and extend the number of cobenefits to be harnessed. If the invasive plant species can act as hyperaccumulators for particular contaminants, they are known to be useful for phytoremediation. They possess some desirable characteristics to act as effective phytoremediation agent, including high growth rates and ability to adapt for new environments. However, the threat that generates by them for the natural environment must be evaluated carefully, before their use as phytoremediation agents. Therefore the use of native plant species for phytoremediation has been evaluated by a few researchers (Pandey et al., 2015; Pandey and Singh, 2011). Native plants will not pose a negative impact on the particular environment but involve to increase the biodiversity. Moreover, native plant species might provide socio-economic benefits for local communities. However, the most recent approach for phytoremediation is the use of transgenic plants. Plants incorporated with new genes which express desirable features for pollutants uptake, metabolism, and/or accumulation inside plant tissues usually have certain advantages over the traditional plant species used. Besides, different countries made their own policies toward the use of genetically manipulated crops for the food industry, use of this kind of plants for phytoremediation is still questionable.

For assessing the effectiveness of plants as agents of bioremediation, the status of edaphic factors and soil macro- and micro-organism communities cannot be neglected. In order to produce high biomass for the success of phytoremediation, sufficient supply of essential plant nutrients is vital. Additionally, the majority of plant species rely on symbiotic organisms, such as mycorrhiza and plant growth, promoting bacteria. Primarily, these interactions are beneficial for the survival of plant species as well as for the high biomass production, which are essential for effective phytoremediation. Therefore future research works should address the above issues in order to fill knowledge gaps to increase the efficiency of phytoremediation for contaminants removal from E-waste contaminated sites.

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