Chapter 6
E-waste: Global Scenario, Constituents, and Biological Strategies for Remediation

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Abstract Global technology development and industrialization have led to the increased usage of electronic gadgets. Electronic waste or e-waste is one of the emerging environmental issues in the developing countries. Much of the e-waste globally generated is recycled in the unregulated informal sector and results in significant risk to environmental health. These wastes also consist of economically valuable minerals such as copper, silver, and gold. The multitude of toxic heavy metals present in the components of discarded electrical and electronic equipment such as cadmium, arsenic, antimony, chromium, lead, mercury, selenium, beryllium, brominated flame retardants, PAHs, and PCBs pose threats to the environment. The usage of microbes and plants in minimizing the toxicity of chemicals and metals in the environment is eco-friendly and cost effective. This chapter provides a concise overview of the volume of e-waste generated globally, disposal and reuse/recycle practices; forecasts e-waste production, and discusses environmentally sustainable remediation strategies. The principles, advantages, and disadvantages of bioleaching, biosorption, bioaccumulation, bioprecipitation, biomineralization, and phytoremediation techniques, which are recognized as biological strategies for remediation of contaminants released into different environmental matrices are presented.

Keywords Bioaccumulation · Bioleaching · Biomineralization · Bioprecipitation · Biosorption · Electronic waste · Phytoremediation

6.1 Introduction

Electronic wastes (e-wastes) assume growing pollution concerns globally, due to the occurrence of a range of toxic substances (Kiddee et al. 2013). The pollution of soil ensuing from offensive e-waste recycling might appreciably alter the soil microbiota

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(Liu et al. 2015). Unrestrained e-waste recycling releases xenobiotic compounds as well as heavy metals into the environment. These objectionable compounds may be disseminated, bioaccumulated/biomagnified resulting in deleterious effects on human health (Man et al. 2013). Generally, many of the persistent materials are capable of undergoing long-range transport via air/water and pressurize the ecosystems and living organisms located at far of distances from the recycling areas (Wang et al. 2011). Farmland soils collected from nearby roads and the dismantling workshops of e-waste recycling areas in South China showed that the concentrations of polybrominated diphenyl ether (PBDE) were subject to complex environmental processes (Luo et al. 2009).

Conventional physical dismantling methods such as crushing, jigging, shaping, and electrostatic separation are in wide usage for handling PCBs. Acid washing is a hydrometallurgical method. Heating and smelting are the pyrometallurgical technique (Awasthi et al. 2016a). E-waste recycling done in workshops include removing the outer coverings, shredding into pieces, changing their state by melting, flaming, discarding the non-usable components, and trading. These activities might enhance contamination of the ambient environment by heavy metals. Moreover, contamination of the surface soil may be limited by the extent of recycling area, type of soil, and physicochemical properties of soil (Fujimori and Takigami 2014). Unsophisticated recycling e-wastes by physical separation and incineration lead to accumulation of heavy metals in the environment (Kyere et al. 2017). Open burning and open storage of e-wastes should be barred and sustainable wastewater treatment strategies should be implemented at each workshop to decrease contamination by dioxin-like compounds from e-waste (Suzuki et al. 2016). Urban biomining implies the use of microorganisms for extracting and recovering metals from terminated products, electronic and electrical wastes, and exhausted batteries (Nancharaiah et al. 2016).

Inadequate legislations coupled with unemployment paved the way for quick rise of informal e-waste handling centers in developing countries. Contaminants move through the food chain by means of root plant translocation system and to the human body thereby threatening human health (Awasthi et al. 2016a, b). Toxic heavy metals that get accumulated in the water and sediments can have hazardous implications on associated life forms. We understand that surface as well as bottom sediments offer habitat and food for all kinds of associated organisms. There are chances for either direct or indirect contamination of aquatic ecosystems by heavy metals leading to bioaccumulation. Moreover, atmospheric deposition of heavy metals by sedimentation could impact human health as well (Kyere et al. 2017). Abandoned e-waste recycling areas pose serious ecological risk. One of the best possible solutions to address e-waste contamination might be remediation of polluted soil and water (Wu et al. 2015). Risks factors associated with unsustainable waste management practices offers scientific recycling as a viable alternative practice (Echegaray and Hansstein 2017). EPA has estimated globally an increase of 5–10% in e-waste generation per year. Our challenge lies in identifying and developing most innovative, cost-effective, and eco-friendly solutions; this method can be used to decontaminate the polluted environments and convert it into proper functioning ecosystems, which can support life for present and future generations. The present article summarizes the role of microbes in innovative alternative clean-up technologies for the removal of e-waste. Currently, the world is in the quest for novel approaches that could address escalating forms of anthropogenic wastes. Extended Producer Responsibility (EPR) is one such move toward e-waste management. As defined by OECD “EPR is an environmental policy approach in which a producer’s responsibility for a product is extended to the post-consumer stage of the product’s life cycle, including its final disposal” (OECD 2001). Subsequent to the “Polluter-pays Principle,” it might be comprehended according to the EPR policy, considering the environmental impacts of the products manufactured, the expenditures on treatment and disposal of the end products should be incorporated into the market price of the product.

6.2 State-of-the Art Picture of E-waste Management

Today, globally waste produced from Electric and Electronic Equipment’s (WEEEs) is reported to be growing annually greater than ever from 3% to 5% (Cucchiella et al. 2015). It is estimated that globally approximately 49.8 million tons of e-waste is generated in 2018 (Cui and Anderson 2016). In India, it was jointly estimated by UNEP and United Nations University (UNU) by the year 2020, e-waste from old computers might record a growth of 500% (Borthakur and Govind 2017). About 6.8 kg of e-waste per person was generated in 2012 according to the estimates of UNEP. The transboundary movement of e-waste from the Northern hemisphere to the Southern hemisphere poses a serious threat to the environment. Several urban areas in Africa have become containers for rejected e-waste from developed countries. As a matter of fact, the industry surrounding e-waste dismantling is known to ruin the quality of ambient environment (Daum et al. 2017). Here, it is apparent to understand global e-waste trading. Therefore, significant regulations on transboundary movement of e-waste from OECD countries to non-OECD countries were imposed by the Basel convention (Wath et al. 2011). To enable environmentally friendly management of used and end-of-life computing equipment, the Partnership for Action on Computing Equipment (PACE) has been initiated by the Parties to the Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal. PACE has framed guidelines on deciding the basis of the functionality of end-use computers and computer components (Perkins et al. 2014; UNEP 1992). However, many independent studies suggest higher concentrations of Persistent Organic Pollutants (POPs), such as polychlorinated biphenyls (PCBs), in subtropical and tropical regions of the world (Breivik et al. 2015). One of the first countries to implement formal e-waste management regimen was Switzerland that recycled 11 kg/capita of WEEE against the 4 kg/capita goal set by EU (Wath et al. 2010). As a matter of fact, the discarded end-of-life computers from Japan are reused in China, while home appliances from Japan are reused in Southeast Asia. Furthermore, we understand that the e-waste scrap produced in Asia

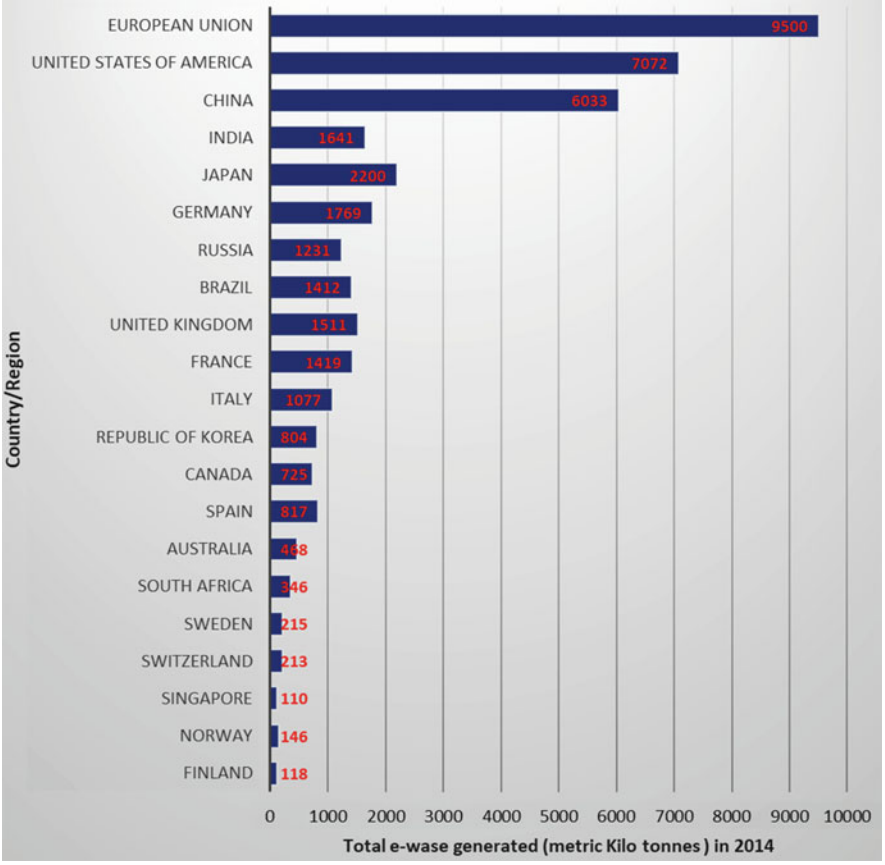

Fig. 6.1 Global e-waste generation based on UNU 2015

is recycled in Guangdong Province of China (Shinkuma and Nguyen 2009). According to an estimate of the European Environment Agency, annually about 1.3 million tons of rejected EEE are shipped from the EU to Asia and Africa (Lundgren 2012). Instances of water contamination have been reported in areas close to e-waste recycling towns in China. Furthermore, escalated levels of dissolved metals were found contaminating the sediments in the rivers nearby e-waste recycling town of Guiyu (Chan and Wong 2013). Mixed contamination of organic and inorganic contaminants in the soil was identified in several studies owing to unscientific recycling of emerging anthropogenic wastes. Presently, there is an urgent need for transformation of land use patterns likely to pose threat to the human health as well as wildlife. Consequently, novel soil remediation techniques that can address these issues are essential (Ye et al. 2015). Subsequently, it is imperative to consider the assorted global experiences and advance comprehensive schedules to discourse the e-waste catastrophe pertaining to any growing economy with prime importance (Borthakur and Govind 2017) (Fig. 6.1).

6.3 E-waste Generation in India

In the Indian context, formulating a single widely accepted e-waste management strategy is quite challenging owing to the presence of a vast diaspora of sociocultural, economic, political, technological, infrastructural, and environmental considerations. However, instead of learning from extraneous experiences in e-waste management we can study from our own proficiencies and frame an inclusive strategy for sustainable e-waste supervision. The highest contribution to waste electrical and electronic equipment (WEEE) in the country is given by West Bengal, Uttar Pradesh, Tamil Nadu, Delhi, Andhra Pradesh, Maharashtra, Karnataka, Punjab, Gujarat, and Madhya Pradesh. Among the total e-waste generated in the country, southern, northern, and eastern regions account for 30%, 21% and 14%, respectively, while western India accounts for the largest volume at 35% (Needhidasan et al. 2014). However, the existing practices of storage, processing, recycling, and disposal of e-waste handling are likely to harm human health and the environment (Borthakur 2015). In India, approximately an 18-fold increase in the usage of mobile phones is expected by 2020 (Perkins et al. 2014). Therefore, framing strategies and implementation in the area of solid waste management is supposed to be one of the most demanding environmental glitches facing local governments in urban India (Cornea et al. 2017). The sale of secondhand electronics items operated from the outskirts of the megacities has a profitable market in the country (Ongondo et al. 2011). Though presently almost 138 formal e-waste recycling setups have come up to mitigate the e-wastes, an appreciable quantity of generated e-wastes is not reaching the recycling centers (CPCB 2014). No validated data regarding e-waste generation in the country is available till date. Consequently, a research gap is visualized on the extrapolation of e-waste generation and possibilities of projected waste disposal patterns in country (Dasgupta et al. 2017).

Enormous quantities of e-waste from developed countries is imported to developing countries like India. Among the total e-waste generated in India 65 cities generate more than 60%. Therefore, the Indian government plans to legislate new regulations that make a producer/manufacturer of equipment accountable for the gathering and proper disposal of e-waste generated when the product is discarded. As per the reports of Confederation of Indian Industries, the total out-of-date electronic and electrical equipment waste generated in India has been valued to be 1,46,000 tons per year. In this case, 22% PCs e-waste generated by households, 78% accounts business sector, approximately 1050 tonnes per year of computer wastes comes from manufacturing as well as retailing sectors. The management and handling of waste in India is currently governed by legislation such as the Environment (Protection) Act of 1986, and Hazardous Material (Management, Handling and Transboundary Movement) Rules of 2008 (Chauhan and Upadhyay 2015). Usage patterns of various e-items, e-waste generation, and disposal, jointly designed a composite concern where buyers desire to reap maximum profit from the clearance arrangement such as reusing and recycling (Dasgupta et al. 2017).

6.4 Constituents of E-wastes

The main components of e-wastes include wood, glass, plastics, ferrous and non-ferrous metals, rubber, concrete and ceramics, plywood, printed circuit boards (PCB), and other items. The presence of elements like arsenic, cadmium, lead, mercury, selenium, and hexavalent chromium and flame retardants beyond threshold quantities of e-waste classifies them as hazardous wastes. Among the several metals associated with discarded equipment, iron and steel constitute about 50% of the total e-waste generated followed by plastics (21%), non-ferrous metals (13%) including other constituents. Non-ferrous metals consist of metals like aluminum (Al), copper (Cu), and precious metals, for example, gold (Au), silver (Ag), palladium, and platinum (Needhidasan et al. 2014). Hazardous heavy metals and organic compounds, mainly polycyclic aromatic hydrocarbons (PAHs), polychlorinated and polybrominated dibenzo-*p*-dioxins (PCDDs and PBDDs), hexabromo cyclododecanes (HBCDs), polybrominated diphenyl ethers (PBDEs), polychlorinated and polybrominated biphenyls (PCBs and PBBs), dechlorane plus (DP), and polychlorinated and polybrominated dibenzofurans (PCDFs and PBDFs) are also found more than permissible levels at the e-waste dumping sites (Pramila et al. 2012). Printed circuit boards (PCB) of mobile phones and computers are mostly copper and other metal-containing materials. The existence of pollutants in mixtures in the nature renders pollution abatement a complex task, especially when a gradient of contamination reaches to the agricultural soils from the hot spots of contamination (Zhang et al. 2012) (Fig. 6.2).

PCBs can associate with more than 40 elements, including some hazardous ones: Co, In, Zn, Al, Pb, Ag, B, C, H, K, N, O, F, S, Au, Ti, Pd, Fe, Mn, Cu, Ni, Sn, and Sb as well as precious metals such as gold, silver, and palladium (Arshadi and Mousavi

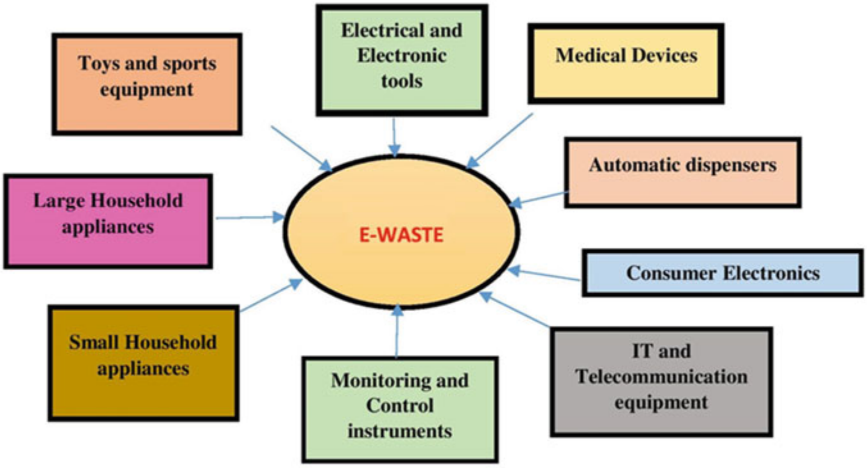

Fig. 6.2 Sources of e-waste generation

Table 6.1 Components of e-wastes

Components	Constituents
Flat screen monitors and switches	Mercury
Printed circuit boards	Lead oxide and cadmium
Cathode ray tubes	Lead and cadmium
Plastics from printers, key boards, monitors	Phthalates
Capacitors and electrical transformers, printing inks	Polychlorinated biphenyls
Plastic cable casings, printed circuit boards	Brominated flame retardants
Cable insulation/coating	Poly Vinyl Chlorides (PVC)
Batteries used in computers	Cadmium

2015). Plastics present in cell phones naturally contain a blend of polycarbonate and polyamide. PBDEs belong to brominated flame retardants (BFRs) that can be utilized in numerous polymeric materials like circuit boards, casings, wires, cable coatings, textiles, resins, and additional substrates to decrease their fire-related hazards. The fourth conference of the parties conducted during May 2009, amended the Stockholm Convention on persistent organic pollutants (POPs) by adding two groups of PBDEs namely Hexa- and Hepta-BDEs, and Tetra- and Penta-BDEs to Annex A (Elimination) of the Convention (Anh et al. 2017). E-waste comprehends 60% of metals, about 30% plastics, and the rest hazardous pollutants of 2.70% (Widmer et al. 2005). Since the lifetime of a computer is around 2–5 years, it is projected that around 17 million computers are thrown away annually. Supposing that the mass the central processing unit (CPU) of computers is around 3 kg, we can evaluate that approximately 50 million kilograms of CPUs get rejected annually. The amount of gold in 1 ton of PCBs from computer amounts to ~17 tons of ores where return outcomes display ~40 wt % of the output was copper (Arshadi and Mousavi 2015) (Table 6.1).

6.5 Effects on Soil Microbial Communities

Soil microbes perform dynamic functions in the ecosystems. These communities may be strongly organized by land-use patterns related to e-waste recycling, which can surge the heavy metal concentration in soils (Wu et al. 2017). Basic e-waste recycling activities discharge enormous quantities of persistent organic pollutants (POPs) and heavy metals into ambient soils, affectating considerable peril to the ecosystems and human health. Microbes capable of metabolizing POPs in soils play essential roles in POPs remediation (Liu et al. 2015). Bioremediation can expand the e-waste management horizons in a sustainable manner. All such strategies should focus on the organic and inorganic portions of the e-wastes. Organic fraction composed of a variety of thermo- and thermosetting plastics. These plastics might be halogenated where soil microbes get involved in the process of dehalogenation. Leaching of inorganic portions of both metallic and non-metallic components can be managed by microbes (Pant et al. 2018). High persistence, toxicity, and bioaccumulation resulted in higher attention for compounds such as PCBs. PBDE patterns from an e-waste recycling site in South China implied that the PBDEs in farmland soils have been subjected to complex environmental processes (Luo et al. 2009). *Microbes such as Solibacter*, *Nitrososphaera*, and *Nitrospira* dominated in e-waste recycling sites (Wu et al. 2017). High-throughput 16S rRNA gene sequencing showed that *Acidobacteria, Bacteroidetes, Chloroflexi, Deltaproteobacteria*, and *Firmicutes* dominated the river sediment microbial assemblages consistently polluted by e-waste (Liu et al. 2018). Enhanced PCB degradation was due to the amplified PCB biostimulation of microbial communities subsequent to the accumulation of plantation and β-cyclodextrin. Besides, experimental results suggested that PCB elimination was mainly subsidized by microbial degradation rather than plant uptake or abiotic dissipation (Luo et al. 2009). The diversity of bacterial communities in the soil around an e-waste recycling workshop in the Taizhou in China was reported gradual change in soil bacterial diversity along the polychlorinated biphenyls pollution gradient (Tang et al. 2013). Concentrations of most of the heavy metals such as cadmium (Cd), chromium (Cr), lead (Pb), nickel (Ni), and zinc (Zn) in soil, water, and plant samples during the wet and dry seasons in and around the largest e-waste dumping site in Nigeria, Alaba International Market in Lagos exceeded maximum permissible levels (Olafisoye et al. 2013).

6.6 Biological Remediation Strategies

Chemical methods assure advanced recovery of metal within a short duration. Requirement of huge quantities of chemical reagents, risks involved in operation and handling including chances for secondary contamination can be understood as the drawbacks in chemical methods. Though physical or mechanical method can rapidly recycle electronic wastes they are costly and it is tough to detach impurities from metals. Even from depleted low-grade wastes, we can recover metals using relatively simple operational technology, energy efficiency, low cost, environmental compatibility, and efficiency in recovery of metals (Priya and Hait 2017; Awasthi et al. 2016a). The occurrence of organic pollutants and epoxy layer coatings on metals should be detached to render metals accessible for microbial attack to ensure quicker extraction and recovery. Microorganisms such as bacteria, yeast, and algae are identified to persist in waste-holding environs due to its aptitude to decrease, amass, confiscate, captivate, and oxidize dissimilar kinds of waste materials making it meagerly soluble and effortlessly precipitated so that their toxicity gets reduced (Varjani et al. 2018) (Fig. 6.3).

Biological methods such as bioleaching, biosorption, bioaccumulation, biotransformation, bio-oxidation, biomineralization, and microbially improved chemisorption of metals can be used in the removal of toxic metals from e-wastes (Patel and Kasture 2014; Dixit et al. 2015). Though bacteria are competent in leaching metals from electronic wastes, the capability of fungus and algae is not much explored in this field. Since the biosorption capacity of fungus is quite efficient for heavy metals,

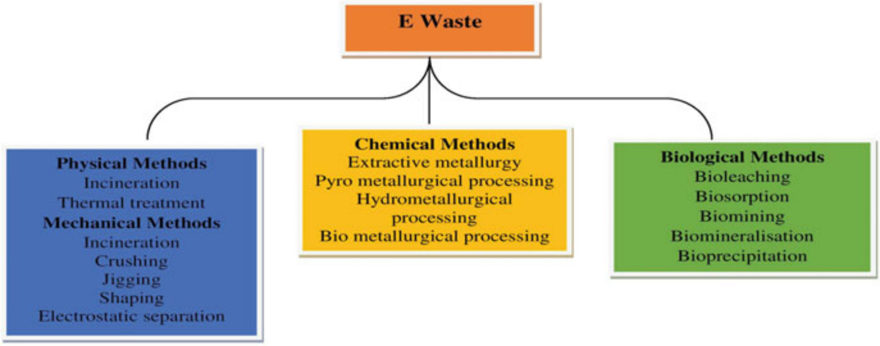

Fig. 6.3 Strategies applicable for the handling e-wastes

bioleaching studies can be performed with fungus, which has efficient enzymes to enhance utilization (Chatterjee and Abraham 2017). Bioaccumulation is the active mechanism of metal uptake, while biosorption is the passive mode in which the dead biomasses of the microorganisms are utilized for sorption (Volesky 1990). Bio-oxidation is the process of extraction of metals, mainly gold from ores, by oxidizing the matrix in which the metals are fixed. Basically, the metals are made available for extraction in this process. In large-scale stirred tanks bio-oxidation process recycled to discharge gold (Nancharaiah et al. 2016).

6.7 Bioleaching

Microbial leaching is a pragmatic method for extracting metals in solid state from e-waste. The natural capability of microbes to oxidize or utilize organic and inorganic substrates is exploited for melting the metals. Autotrophic bacteria, heterotrophic bacteria, and heterotrophic fungi are the three key microbial groups involved in this mechanism (Awasthi et al. 2016a; Karwowska et al. 2014). We can understand bioleaching as a process in which microbes interact with the metals for extraction and purification (Gerayeli et al. 2013). Chemical and biological leaching has its own pros and cons. Technical, economic, and environmental reasons are important for choosing one process over the other. Hybrid methodology helps to overcome the glitches associated with chemical and biological extraction techniques for the metals present in e-waste (Needhidasan et al. 2014). Acidophilic microorganisms are vital for leaching heavy metals from wastes (Hong and Valix 2014). They thrive in acidic pH (2.0–4.0) and help in dissolving the metals. Among the bacteria, *Acidithiobacillus ferrooxidans, Acidithiobacillus thiooxidans, Leptospirillum ferrooxidans*, and *Sulfolobus* sp., are well-known consortia for the bioleaching activity while fungal genera such as *Penicillium* and *Aspergillus niger* help in metal leaching process (Mishra and Rhee 2010). Bioleaching, involving microorganisms such as *Chromobacterium violaceum*, may allow metal recycling (Tay et al.

2013). The bacteria isolated from *Hymeniacidon heliophila* sponge cells showed bioleaching activity and these bacteria could be used as a copper recovery tool from e-waste (Rozas et al. 2017). Au tolerance of *Aspergillus* species could be a suitable indicator for selecting filamentous fungi able to cause bioleaching of gold from WEEE (Madrigal-Arias et al. 2015). The efficiency of the bioleaching process is predisposed by the effects of abiotic factors plus the metallic composition of the waste, with special reference to their secondary reactions (Valix 2017). Biological leaching, on the other hand, is comparatively a low-cost method while it is time consuming and complete recovery of the metal may not be practically feasible sans biological leaching (Pant et al. 2012). Biochar with redox activity can be used to enhance the bioleaching efficiency of metals from a basic e-waste in order to avoid the disadvantages of being time consuming or having a moderately low efficiency. Iron-mediated bioleaching was significantly promoted by biochar and its leaching time was decreased by one-third compared with that of a biochar-free system (Wang et al. 2016). Fungi interact with gold by mobilizing it through a mechanical attack as well as through biochemical leaching by the production of cyanides. Moreover, fungi are also able to release Au through the degradation of cyanide from aurocyanide complexes. Subsequently, fungi can localize gold through biosorption, bioaccumulation, and biomineralization as nanoparticles. The diversity of mechanisms of gold recycling using fungi combined with their filamentous lifestyle, which allows them to thrive in heterogeneous and solid environments such as e-waste, makes fungi an important bioresource to be harnessed for the recovery of gold (Bindschedler et al. 2017) (Table 6.2).

6.8 Biosorption

Biosorption is a physicochemical and metabolically independent process. Mechanisms include absorption, adsorption, ion exchange, surface complexation, and precipitation (Fomina and Gadd 2014). It is a biotechnological revolution, low-cost tool for recovery of precious metals from aqueous solutions. Diverse natural biomaterials such as algae, fungi, bacteria, actinomycetes, yeast; biopolymers, and biowaste materials are acknowledged to bind to the metals (Das and Das 2013). The benefits of an ideal biosorption process include low cost, short operation time, absence of toxicity limitations, absence of requirements for nutrients, avoidance of sudden death of biomass, and easy mathematical modeling of metal uptake by reactors. Passive biosorption also has some disadvantages, such as early saturation and limitation in biological process (Hansda and Kumar 2016). Biomaterials such as rice husk, coconut shell, plant barks, leaves, sawdust, sugarcane bagasse, and peat moss have received much interest (Michalak et al. 2013). The mechanism of biosorption is complex. Biological ligands, biosorbents, characteristics of the targeted metals and characteristics of the metal solution drive these mechanisms (Deng and Wang 2012). Selective biosorption of gold from printed circuit board was achieved by using the combination of ammonium thiosulfate (AT) and *Lactobacillus*

Table 6.2 List of major microbes and metal extraction mechanisms

Metal chelating microbial groups	Name of organisms	Metal extracted	Mechanism	References
Iron oxidizers	*Acidithiobacillus ferrooxidans* *Leptospirillum ferrooxidans* *Leptospirillum ferriphillum*	Cu, Zn, Ni, Pb, Cd	$2Fe^{2+} + \frac{1}{2}O_2 + H^+ \rightarrow 2Fe^{3+} + H_2O$ $Cu^0 + 2Fe^{3+} \rightarrow Cu^{2+} + 2Fe^{2+}$	Dave et al. (2018), Awasthi et al. (2016a), Bas et al. (2013)
Sulfur oxidizers	*Acidithiobacillus thiooxidans* *Sulpholobus* spp.	Cu, Zn, Ni, Al	$2S^0 + 3O_2 + 2H_2O \rightarrow 4H^+ + 2SO_4^{-2}$	Dave et al. (2018)
	Leptospirillum ferriphilum *Sulfobacillus thermosulfidooxidans*	Cu		Wu et al. (2018)
Cyanogenic organisms	*Chromobacterium violaceum Pseudomonas aeruginosa* *Pseudomonas florescence* *Marasmius oreades*	Au, Ag, Pd, Pt	$NH_2CH_2COOH \rightarrow CN^- + CO_2 + 4H^+$	Ilyas et al. (2014)
	Bacillus megaterium	Au, Cu		Arshadi and Mousavi (2015)
	Chromobacterium violaceum	Au		
Organic acids producers	*Aspergillus niger* *Penicillium simplicissimum*	Cu, Zn, Ni, Pb, V, Mo, Al, Co, Li		Dave et al. (2018)
	Acidithiobacillus thiooxidans and Acidithiobacillus ferrooxidans	Cu		Liang et al. (2010)

acidophilus. This process might include a unique leaching-sorption method for gold recovery from AT leachant by the proposed combination (Sheel and Pant 2018). Gold biosorption from leached solutions using chitin as biosorbent enabled about 80% of the gold recovery. This study reported that precipitation followed by biosorption resulted in the best gold recovery, because other species were removed from the leachate solution in the precipitation step (Cortes et al. 2015). Green algae are highly abundant biomaterials employed as useful biosorbents in many studies. *Cladophora hutchinsiae* the biosorbent used for removal of highly toxic chemical such as uranium (Bagda et al. 2017). Novel bacterial strain *Halomonas* BVR 1 isolated from electronic industry effluent is very effective in adsorbing cadmium (Rajesh et al. 2014). Biosorption technique using agricultural or industrial wastes can be employed to recover heavy metals from leachate followed by their precipitation as hydroxides. Combinatorial approach of these two processes provides solutions to the shortcomings of metal leaching. Amended cellulosic materials with specific functional groups, such as carboxyl, amino, and sulfo, are considered conductive to the sustainable development and long-term economic interests (Varshney et al. 2017).

6.9 Biomining

Biomining is an industrial-scale biotechnological process meant for extracting base metals from sulfidic ores. Presently, biomining accounts for about 20% and 5% of the world production of Cu and Au, respectively. Industrial biomining uses oxic conditions and acidophilic iron- or sulfur-oxidizing microorganisms (e.g., *Acidithiobacillus ferrooxidancs*, *At. thiooxidans*). These microbes produce ferric iron which is an oxidant and sulfuric acid, the promoter of dissolution (Nancharaiah et al. 2016). Biomining is now used chiefly to leach copper sulfides and as an oxidative pretreatment for refractory gold ores, though it is also used to recover other base metals, such as cobalt, nickel, and zinc. Current developments have included using acidophiles to process e-wastes, to extract metals from oxidized ores and to selectively recover metals from process waters and waste streams (Johnson 2014). Chemolithotrophs such as *Acidithiobacillus and Leptospirillum* are the most commonly used genera for the biomining of metals from dust. *Acidithiobacillus ferrooxidans* extracted up to 70% of Zn from Fe–Mn alloy industrial dust by oxidative bioleaching (Sethurajan et al. 2018). The microbial solubilization of metals by biomining is positively used in industrial processes to extract numerous metals such as copper, gold, and uranium (Jerez 2017). Biomining organisms are able to grow lithotrophically by oxidizing ferrous iron and/or elemental sulfur as electron donors to produce ferric iron and sulfuric acid, which attack sulfide minerals. Some biomining microbes can also grow autotrophically using CO_2 for growth, whereas others are heterotrophic and thus need an organic carbon source (Schippers 2007). The most frequently used tactics for commercial-scale biomining are based on bioreactors, heaps, and dumps (Kaksonen et al. 2017). Two other engineering designs are used in biomining operations. Stirred tank bioreactors are used almost exclusively for bio-oxidation of refractory gold concentrates in which the fine gold particles are enshrouded by sulfide minerals. Most current commercial operations use the BIOX® process and operate as continuous feed systems, processing between 40 and >8000 tons of concentrate/day (Brierley and Brierley 2013; Rawlings 2002). All biomining operations work under non-sterile conditions which preclude or restrict the use of genetically engineered microorganisms. While pure cultures of bacteria or archaea can degrade sulfide minerals, it is now well recognized that bioleaching and biooxidation are mediated by consortia of acidophilic prokaryotes. These have been categorized as: firstly, ferric iron-generating prokaryotes which produce the mineral oxidant; secondly, sulfuric acid-generating autotrophs which maintain the low pH environment essential; and lastly, heterotrophic and mixotrophic prokaryotes, which degrade organic compounds seeped from autotrophic iron oxidizers and sulfur oxidizers, thereby escaping potential toxicity issues (Johnson and Hallberg 2008). Erüst et al. (2013) reviewed the possible applications of biohydrometallurgy to recover metals from spent batteries and catalysts.

6.10 Bioaccumulation

Bioaccumulation is a biotechnological approach for the removal of heavy metals where living biomass takes up and transports heavy metals. It relies on intrinsic biochemical and structural properties, physiological and genetic adaptation, environmental modification of metal specification, availability, and toxicity (Jaafar et al. 2015). It is a toxicokinetic process that affects the sensitivity of living organisms to chemicals. Organisms can normally resist concentrations of chemicals up to certain levels, beyond which these chemicals become toxic and endanger the organism (Mishra and Malik 2013). Efforts on engineering metal-resistant microorganisms have been conducted mainly on mesophilic strains for bioremediation purposes, such as genetically engineered *Escherichia coli* JM109 for the accumulation of mercury, nickel, and cadmium by overexpression of a metal transport system and a metallothionein or a polyphosphate kinase and metallothionein, a phytochelatin synthase gene, and a heavy metal ATPase gene. Genetically modified strains of *Corynebacterium glutamicum* for arsenite accumulation *E. coli* BL21 for cadmium accumulation by incorporating glutathione synthesis genes, a serine acetyltransferase gene. *Pseudomonas putida X4* for cadmium biosorption by surface display of metallothionein (Gumulya et al. 2018). During augmented metal exposure, bacteria produce metal-binding proteins such as metallothioneins that can bind with metals and transport them into the cell. Several organisms have been reported for the study of bioaccumulation for increased levels of pollutants, including plants, fungi, fish, algae, mussels, oysters, and bacteria (Mosa et al. 2016). The exceptional ability of the GeoChip microarray technique coseals 424,000 genes in over 4000 functional groups elaborated in various significant biological processes. Further, this technique can be applied to search the bioaccumulation capability of several microbial groups to uranium (Van Nostrand et al. 2009).

6.11 Bioprecipitation

Alteration in the ionic equilibrium of metals owing to the addition of certain chemicals. This process is unlike coagulation and flocculation. Concentrations of the metals in the solution and pH determine the removal efficiency of metals. Precipitation includes stages like nucleation, growth of nucleus, aggregation, and crystallization. The chief drawbacks of these processes are sludge generation and pH adjustment (Sethurajan et al. 2018). Ultimately, this process results from the excretion of special proteins like thiol groups rich special proteins/proteins with less molecular weight namely metallothioneins and phytochelatins from bacteria that reacts with metal ions present in solution to yield insoluble metal compounds (Hansda and Kumar 2016). The possibility of selective recovery of metals from multimetallic leachate can be understood as a significant merit of bioprecipitation systems. By altering, the system pH, metals can be selectively precipitated as metal sulfides, since metal sulfide formation is dependent on the solution pH (Sethurajan et al. 2018).

6.12 Biomineralization

This is a process in which harmful metal ions associate with anions or ligands formed from the microbes to form precipitation (Tabak et al. 2005). Applications suggest the potential to remove these metals from contaminated water as well as sequester them in a reusable form. Biomineralization can be studied with respect to phylogenetically diverse microorganisms isolated from pristine and contaminated environments (Lens 2016). Studies including fungal genera reported that gold can be immobilized by biosorption, bioaccumulation, and biomineralization (Bindschedler et al. 2017) (Table 6.3).

6.13 Phytoremediation for Electronic Waste

Green technology utilizes the natural potential of plants to remediate contaminated surface water, soil, and sediments (Kathi and Khan 2011). Utilizing plants to eliminate toxic metals and metalloids is found to be limited by time-consuming remediation process as well as phytotoxicity of heavy metals (Dhankher et al. 2012).

Table 6.3 List of microorganisms identified for various biological extraction of metals

Name of the microorganism	Name of the toxic metal removed	References
Bioleaching		
Acidithiobacillus thiooxidans *Micrococcus roseus* *Thiobacillus ferrooxidans* *Aspergillus fumigates* *Aspergillus niger*	Arsenic, Lead Cadmium Arsenic, Lead Arsenic Cadmium, Lead	Patel and Kasture (2014)
Acidithiobacillus ferrooxidans *Acidithiobacillus thiooxidans* *Sulfobacillus thermosulfidooxidans* *Sulfobacillus thermotolerans* *Leptospirillum ferrooxidans*	Copper	Makinen et al. (2015)
Sulfobacillus thermosulfidooxidans *Thermoplasma acidophilum*	Al, Cd, Cr, Cu, Pb, Zn	Ilyas et al. (2014)
Acidithiobacillus ferrivorans and Acidithiobacillus thiooxidans	Cu	Isildar et al. (2015)
Biosorption		
Bacillus sphaericus *Pseudomonas aeruginosa* *Myxococcus xanthus* *Rhizopus arrhizus* *Streptoverticillium cinnamoneum* *Saccharomyces cerevisiae* *Pseudomonas putida* X4 *Bacillus subtilis* *Magnetospirillum gryphiswaldense* *Rhizopus arrhizus (F)* *Acidithiobacillus ferrooxidans*	Chromium Uranium Cadmium, Uranium Lead Cadmium Cadmium	Patel and Kasture (2014) He et al. (2012)
Ecklonia maxima (Algae) *Synechocystis* sp. *Chlorella vulgaris,* *Scenedesmus obliquus*	Zinc Cadmium, Copper, Lead Copper, Nickel, Chromium	Chojnacka et al. (2005) Gajendiran and Abraham (2015)
Bioaccumulation		
Deinococcus radiodurans *E. coli* JM109 *Corynebacterium glutamicum* *Plectonema boryanum UTEX 485 (Cyanobacteria)*	Lead, Cadmium Mercury, Nickel, and Cadmium Arsenic Gold	Jaafar et al. (2015) Gumulya et al. (2018) Villadangos et al. (2014) Al-Homaidan et al. (2015)
Biomineralization		
Bacillus fusiformis *Cupriavidus metallidurans* *Desulfotomaculum auripigmentum* *Sporosarcina ginsengisoli* *Aspergillus flavus* *Cupriavidus metallidurans*	Lead Cadmium Arsenic Arsenic Lead Gold	Patel and Kasture (2014) Lengke et al. (2006)
Bioprecipitation		
Thauera selenatis	Selenium	Francis (1998)

The technique of phytoremediation includes numerous processes such as phytoextraction, phytofiltration, phytovolatilization, phytostabilization, and phytodegradation (Alkorta et al. 2004). Biotechnological approaches are currently being used for the phytoremediation of heavy metals and metalloids, such as Hg, Cd, Pb, Se, Cu, and As. Approaches to engineer plants for phytoremediation of heavy metals and metalloids include: (1) manipulating metal/metalloid transporter genes and uptake systems; (2) enhancing metal and metalloid ligand production; and (3) conversion of metals and metalloids to less toxic and volatile forms (Kotrba et al. 2009). This process has been utilized successfully in areas contaminated with PCBs and other organic pollutants (Pramila et al. 2012). Toxic elements can be mobilized and transported (influx) into roots through plasma membrane transporters. They can then be effluxed out of the roots into the xylem and translocated into the shoots. At this stage, plant tolerance to toxic elements may be boosted through manipulation of influx/efflux transporters or by enhancing the levels of chelators. Volatilization of the toxic elements can be achieved through enzymes that modify these toxic elements. Chelators or efflux transporters can also be used to export the toxic elements out of the cytosol and into vacuoles or the cell wall (Mosa et al. 2016; Dhankher et al. 2012). Next generation sequencing was used to study the whole genomes and transcriptomes of several heavy metal-tolerant organisms (Peña-Montenegro and Dussán 2013). Genomics, proteomics, metabolomics, transcriptomics, and phenomics could support the process of identifying the candidate genes that can be later extrapolated for designing plants for phytoremediation. To achieve this end, several approaches have been put forward including transgenic, cisgenic, gene stacking, metabolic engineering, and genome editing (Mosa et al. 2016).

6.14 Conclusions

Toxic constituents present in e-waste needs to be efficiently reduced at the source of generation. This issue can be sustainably addressed using hybrid microbiological processes. However, the efficiency of biological treatments would be enhanced if it is used with a combination of different methods such as with nanoparticles or with some non-polluting biodegraded agents. Therefore, biological methods can be suggested to curtail the e-waste pollution. In the process of reusing wastes generated from fermentation industry, it can be applied for the removal and extraction of metals from the electronic equipment. e-biologics, either produced using microbes or designed with microbial components can be considered as a significant green solution. Reductive bioleaching of oxidized ores and urban biomining of electronic wastes are the recent innovations in the field of biomining. Commercial phytoremediation of heavy metals and metalloids can be fostered by initiating breeding programs to improve the biomass and growth habits of natural hyperaccumulators and breed those traits into non-food, high biomass, fast growing plants for sustainable removal of contaminants. Moreover, a combination of phytoremediation approach with bioenergy ensures twin use of plants for phytoremediation and biofuel production can be considered as a significant option for remediation of contaminated lands.

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