Chapter 18
Bioremediation Approaches for E-waste Management: A Step Toward Sustainable Environment

Toqeer Ahmed, Irfan Liaqat, Rabbia Murtaza, and Anjum Rasheed

Abstract Electronic waste commonly known as e-waste is becoming an important concern all over the world and has life-threatening effects on both human and the environment as it comprises toxic metals and emissions like chlorofluorocarbons. E-waste comprises both hazardous and valued materials demanding distinct management and recycling techniques to evade adverse ecological effect and detrimental impact on human well-being. Inappropriate recycling practices and release of toxic chemicals from the e-waste can damage human health including lung diseases, cancer, and mental and reproductive health. Children are most vulnerable to toxic metals. Transport of hazardous wastes in the form of electronic products from developed to developing countries is increasing health risks, and less attention has been paid on this matter during the past two decades. It is highly recommended to raise awareness about the health hazards related to e-waste. In this chapter, toxicity, health concern, bioremediation approaches for e-waste management (EWM), international regulations, and e-waste issues with reference to Pakistan perspective have been discussed in detail.

Keywords Bioremediation · E-waste management · Sustainable environment

18.1 Introduction

Electronic waste is becoming a prime concern around the globe due to its unsafe disposal and life-threatening health impacts on the biosphere and communal health (UNEP 2007; Song et al. 2014; Balde et al. 2015). The environmental impacts of improper e-waste management have been observed in water, air, and soil because of the release of toxic substances. The extensive industrial processing and chemical handling have raised serious issues for global soil, water, and air through

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contamination of hazardous substances such as xenobiotics, polyaromatic hydrocarbons (PAHs), insecticides, and heavy metals. These contaminants were recognized as poisonous, oncogenic, and mutagenic for living organisms (Tripathi 2011). During the last decade, modification in our lifestyle has hugely impacted the environment, where the need to execute a supplementary sustainable strategy regarding our consumption behaviors appears of much consequence. This trend specially in commercial sectors that are most likely affecting our environment including electronic manufacturing where the lower half-life and the rapidly evolving technology have resulted in higher electronic-waste volumes across the globe. "E-waste comprises of a varied and emerging variety of electronic devices ranging from bulky everyday appliances, like mobile phones, air-conditioners, freezers, audio systems and expendable electronic items to Personal Computers (PC's) disposed of by customers" (Patel and Kasture 2014).

Most of the electronic-waste components are directed to landfills. Their incomplete recyclability, because of substantial configuration along with the inevitable limitations in landfills, has directed to the growth of retrieval practices for their recovery, indicating the importance of electronic-waste recycling, to retrieve valuable constituents other than waste managing aspect. E-waste ranging from urban to industrial slightly differs in physical and chemical properties. E-waste comprises both hazardous and valued materials demanding distinct handling and recycling techniques to evade adverse ecological effect and detrimental impact on human well-being. Although the valuable and base metal recovery is quite possible by recycling practices, the higher labor cost and the firm environmental regulations have limited these activities (Esteve-Nunez et al. 2001). The classification of electronic-waste components with their sources and exposure routes has been shown in Fig. 18.1.

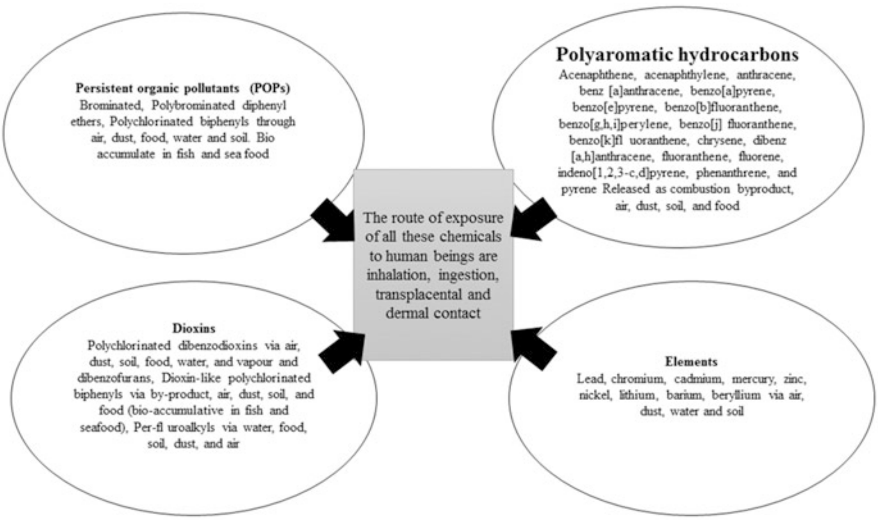

Fig. 18.1 The classification of electronic-waste components with their sources and exposure routes

Many countries have faced immense problems in handling e-waste that is illegally imported or locally produced (Nnorom and Osibanjo 2008). Developed countries ship e-waste to developing countries like Pakistan, India, China, etc. where improper e-waste management techniques are practiced (Sthiannopkao and Wong 2013), while in the Middle East and North African (MENA) countries, 90% e-waste is discarded in landfill and 5% is casually recycled (WAMDA 2018). In low-income countries, e-waste is discarded in unsanitary or uncontrolled sites. These disposal activities of e-waste are generally practiced at Pakistan, India, the Philippines, Nigeria, and China. The wires are burnt to remove copper and plastic, while acid from the batteries is extracted to recover gold, silver, platinum, and palladium from printed circuit boards (PCBs). These e-waste management approaches have been seen in countries, like Pakistan, India, China, Vietnam, Ghana, and the Philippines, to retrieve precious metals where people have scarcity of facilities to protect public health and environment (Leung et al. 2006; SEPA 2011).

In order to treat water and soil from the contamination caused by electronic waste or any other toxic metals or hydrocarbons, persulfate oxidation is used because of its benefits like easy function, stability, no secondary pollution, and greater efficiency (Tsitonaki et al. 2010). Due to its greater solubility, organic compounds are easily oxidized in the aqueous solution and water, thus proving to be a good solution to treat water and soil (Yang and Yeh 2011). The recycling of e-waste generates wastewater issues because it contains toxic metals like Cu, Ni, Cd, Zn, and Pb causing pollution in water, air, and soil (Sojinu et al. 2012; Wong et al. 2007a, b; Deng et al. 2008)

A major challenge in developing approaches for electronic-waste (e-waste) handling is the varying composition of several elements due to quick high-tech advancement, specifically in the electronic components. It is possible to efficiently restore the polluted environment using bioremediation-based methods. Bioremediation usually refers to the degradation of contaminants through microorganisms by acting in parallel or order to completely degrade the hazardous substances that caused risks for the environment and human (Surajit Das 2014). A few microbes are the finest candidates among all microorganisms to eradicate major contaminants in the environment due to their better diversity and adaptability in the environment. Yet, a variety of environmental pollutants have been found to be resistant, due to their partial metabolization or conversion into other xenobiotics by microbes that ultimately again accumulate in the environment. Therefore, it may be more fruitful to find out novel catabolic mechanisms that might result in comprehensive mineralization of these toxic contaminants. Hence, it has become necessary worldwide to take satisfactory actions to regulate the increase in electronic waste as they might increase 50% in the upcoming few years subsequently increasing higher ecological contamination and health risks (Singh and Ward 2004).

18.2 E-waste Composition

Electronic-waste composition depends entirely on the nature and the lifespan of the fragment; telecommunication system and IT scraps comprise a larger quantity of valued metals as compared to scrap from everyday appliances (Tanskanen 2013).

A typical cell phone comprises over 40 components including costly metals such as silver, palladium, and gold; some common metals like tin, copper, and iron; superior metals like lithium, antimony, cobalt, and indium; and remnants like plastic and ceramic (Izatt et al. 2012). The higher use of common metals in electronics like iron is also extensive: around 6 kg iron is utilized commonly in a PC; that means almost 930,000 tons of iron were used for the assembly of personal computers vended in 2007 only. The mutual unit sales in 2007 of cell phones and PCs had further gone up to 3% of the excavated stock of gold (Au), silver (Ag), palladium (Pd), and cobalt (Co) worldwide (UNEP 2009). The worldwide demand of few metals for electronics is almost 80% of indium (for conductive layers in LCD), 50% of antimony (for flame retardants), and above 80% of ruthenium (for magnetic properties). Outdated freezers, refrigerators, and air conditioning elements comprise chlorofluorocarbons (CFCs). The chlorofluorocarbons (CFCs) discharged from objects disposed in landfills contribute majorly to the earth's stratospheric ozone depletion (Scheutz et al. 2004). The harmful contaminants present in e-waste scrap are listed in Table 18.1.

18.3 Toxicity and Public Health Effects of E-waste

E-waste processing has become a universal health problem. Informal and non-standard e-waste processing activities into environment led to malicious chemical leakage. During inappropriate recycling practices, e-waste containing heavy metals are released that results in damaging vegetation, humans, animals, and further environmental resources. E-waste causes the deposition of heavy metals in human tissues, thus posing serious diseases of the liver, lungs, and kidneys (Li et al. 2011). The countries that are utmost affected by inappropriate disposal are India (Bengaluru and Delhi), China (Guiyu and Taizhou), and few African countries (Nigeria, Ghana), in which e-waste has been cast off with minimal or no guiding principle, primarily by means of obsolete technology (de Garbino 2004). Humans are normally unprotected to persistent organic pollutants POPs such as polycyclic-aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), polybrominated diphenyl ethers (PBDEs), dioxin, polybrominated dibenzo-p-dioxins and dibenzofurans (PBDD), polyvinyl chloride (PVC), polychlorinated dibenzo-p-dioxins and dibenzofurans (PCDD), and heavy metals in water, soil, air, and food reservoirs through numerous ways including ingestion, inhalation, and dermal absorption from ignition, expulsions, and industrial facilities. Heavy metals leaked from e-waste reprocessing cannot be broken down into less dangerous end products, unlike organic pollutants

Table 18.1 Hazardous contaminants contained in electronic waste

Electronics scrap	Hazardous substances	E-waste concentration (mg/kg)	E-waste emission per year worldwide (tons)
Condensers, transformers	Polychlorinated biphenyls (PCB)	14	280
Insulation foam, cooling parts	Chlorofluorocarbon (CFC)	–	–
Combustion products	Polycyclic aromatic hydrocarbons (PAHs)	–	–
Products of lower-temperature (*T*) combustion of plastics such as PVCs and others	Polyhalogenated aromatic hydrocarbons (PHAHs)	–	–
Flame retardants	Polybrominated diphenyl ethers (PBDEs)	–	–
Fire retardants	Polybrominated biphenyls (PBBs)	–	–
	Tetra-bromo-bisphenol-A (TBBPA)	–	–
Smoke detectors	Americium (Am)	–	–
Fire retardants, plastics	Antimony	1700	34,000
Si doping material	Arsenic (As)	–	–
Cathode ray tubes (CRTs) Getters	Barium (Ba)	–	–
Silicon-based rectifiers	Beryllium (Be)	–	–
Plastics, batteries, toners,	Cadmium (Cd)	180	3600
Data tapes and floppy disks	Chromium (Cr)	9900	198,000
Wiring	Copper (Cu)	41,000	820,000
Semiconductors	Gallium (Ga)	–	–
LCD displays	Indium (In)	–	–
Solder CRTs, batteries	Lead (Pb)	2900	58,000
Batteries	Lithium (Li)	–	–
Fluorescent lamps, batteries, switches	Mercury (Hg)	0.68	13.6
Batteries	Nickel (Ni)	10,300	206,000
Rectifiers	Selenium (Se)	–	–
Wiring, switches	Silver (Ag)	–	–
Solder, LCD screens	Tin (Sn)	2400	48,000
Solder, LCD screens	Zinc (Zn)	5100	102,000
CRT screens	Rare earth elements	–	–

Adapted from Morf et al. (2007), Robinson (2009) that have biodegradability capacity. Bioaccumulation of electronic-waste elements and their end products (heavy metals) in living organisms can adversely affect human health when their concentration exceeds the minimal level over time (Zeng et al. 2016; Premalatha et al. 2014).

E-waste components influence public health through two different routes that include (1) contamination of food chain, entering of toxic materials into food chain that are released from recycling processes and transferring to animals and humans, and (2) direct occupational exposure of worker to toxic substances working in recycling sites. The dust from all the recycling activities is released into the atmosphere. Fang et al. (2013) proposed special masks for screening of PM 2.5 to mitigate the inhalation of pollutants. Multiple studies suggest that plants and microbes can be used to treat the soil. Extracellular polymeric substances (EPS), proteins, and mucopolysaccharides are released through microorganisms into the soil that forms toxic metal complexes, hence reducing the movement of metals in soil (Rajkumar et al. 2012; Seguel et al. 2015). It has been detected that the exposed population to e-waste has higher frequencies of micro-nucleated bi-nucleated cells. Also, the DNA damage is more common to the people exposed to e-waste. It has been reported that polycyclic-aromatic hydrocarbons, polybrominated diphenyl ethers, and perfluoroalkyls cause adverse outcomes in the infants and neonatals. Multiple chronic disorders in life like type 2 diabetes, obesity, hypertension, and cardiovascular diseases are linked with dioxin-like polychlorinated biphenyls, dioxins exposure, perfluoroalkyls, cadmium, and lead. Similarly, lung damage and lung cancer are associated with certain other compounds that are found in e-waste such as hexavalent chromium, polycyclic-aromatic hydrocarbons, lithium, cadmium, nickel, and arsenic.

Pregnant females exposed to dioxins, polycyclic-aromatic hydrocarbons, polychlorinated biphenyls, polybrominated diphenyl ethers, perfluoroalkyls, and cadmium have suffered with impaired fetal growth, low birth length and weight, preterm delivery, and low head circumference. The chemical constituents of e-waste also affect fertility and reproductive development. Lead causes delayed puberty in girls. The sperm quality of males is affected by polychlorinated biphenyls, TCDD, and perfluoroalkyls, while POPs are also the endocrine disruptors. Other impacts include DNA damage, mental, reproductive, and respiratory issues.

Qu et al. (2007) reported, the direct-exposure of PBDEs on labors in e-waste reprocessing sites and detect the increased levels of PBDEs in the sample of serum groups with the maximum concentration level of BDEs is 3436 ng/g lipid dry weight that is the higher level of BDE in humans until now documented. Similarly, Zhao et al. (2008) measured different organic pollutant levels in hair sample groups including PCBs, PBBs, and PBDEs at 181.99, 57.77, and 29.64 ng/g dry weight, respectively, that are much higher in concentration as compared to reference areas (Zhao et al. 2008; Qu et al. 2007). Wang et al. (2009) detected lead (Pb, 49.5 lg/g) and copper (Cu, 39.8 lg/g) concentration in hair scalp samples. Xing et al. (2009) and Chan et al. (2007) measured PCDD and PCBs in samples of milk of human at 9.50 and 21.02 pg/g, respectively. Ha et al. (2009) detected concentration level of Bi, Cu, and Sb in the hair sample of e-waste recycling labors in India that was much greater than the tolerance level and the concentration levels of tri to tetra-chlorinated (PCBs), tetra-BPhs, tri to tetra-chlorinated (OHPCBs), octa-brominated (OH-PBDEs), and PBDEs in the samples of workers serum were higher than those in serum sample that were taken from individuals existing near the shore area (Wang et al. 2009; Chan et al. 2007; Xing et al. 2009; Ha et al. 2009). These results approve that organic pollutants and heavy metal exposure leaked from e-waste handling processes cause substantial public health risk to labors and native residents specially children and women.

Children are highly vulnerable to toxic metal elements in comparison to adults for few reasons: surplus exposure routes including object-to-mouth, hand-to-mouth, breastfeeding, placental exposures; higher surface area in relation to body-weight, larger ventilation rate per minute relative to body-size, their high basal metabolic rate, comparatively increased food uptake, lower toxin removal rates, and they can inhale much toxic substances; and their tissues and organs are under development stage and so extra sensitive to disturbed cellular processes. Increased levels of cadmium (Cd) and lead (Pb) were found in blood samples of children living near e-waste processing sites (Kiddee et al. 2013).

18.4 Bioremediation Approaches for EWM

Bioremediation is a wide-ranging perception that comprises all procedures and activities that happen to biotransform an environment, previously changed by pollutants, to its native state. Even though the processes that are being used to accomplish the required outcomes differ, they still have similar principles, by using microbes or enzymes, either indigenous or activated by the nutrient addition and optimization of environment or planted into the soil. For gaining energy, microorganisms catalyze energy-producing reactions involving breaking chemical reactions that transfer electrons away from the pollutant. The energy that is acquired from electrons transfer is then devoted along with some added electrons and carbon atoms from the pollutant to produce even more cells. The thermal or physiochemical techniques alone are not as effective as the biological techniques, having greater removal efficiency and being more successful. Bioremediation has now turned out to be a commonly accepted opportunity for the cleaning of polluted soils and aquifers (Pramila et al. 2012).

Currently, four major biological techniques for the cleanup of groundwater and soil are present: (1) native microorganisms' stimulation by adding the nutrients, optimization of redox and pH conditions, etc.; (2) site-specific microorganism inoculation with biotransforming capabilities; (3) immobilized enzymes usage; and (4) phytoremediation procedure to remove or convert contaminants. The specific methods that are being used for bioremediating polluted water and soil include intrinsic bioremediation, slurry bioreactor, land farming, and composting (Bollag and Bollag 1995).

18.4.1 EWM Approaches in Water

18.4.1.1 Bioleaching

Microbes are dynamic in the generation and breakdown of numerous organic as well as inorganic material on earth's surface. Bioleaching is known as the self-capability of microorganisms to alter solid metal composites to its solvable and extractable form. In the metal's bioleaching, three major categories of microorganisms are involved, heterotrophic bacteria (*Pseudomonas* sp., *Bacillus* sp.), autotrophic bacteria (*Thiobacillus* sp.), and heterotrophic fungi (*Penicillium* spp., *Aspergillus* sp.) (Schinner and Burgstaller 1989), as explained in Table 18.2.

Common mechanisms that are involved in bioleaching are acidolysis, complexolysis, and redoxolysis. At 40°C or less, microbes have an ability to remove heavy metals from its iron and sulfide covering mineral concentrates and ores. Through microbial oxidation, iron and sulfide ions are oxidized to produce ferric ion and sulfuric acid, respectively; subsequently these substances can transform insoluble metal sulfides such as copper, zinc, and nickel to soluble metal sulfates that may be simply removed from the final solution (Pham and Ting 2009). The mechanisms of bioleaching process are demonstrated in Fig. 18.2.

Suzuki (2001) discovered that through contact (direct) leaching through bacteria and indirect leaching through ferric ion by bacterial oxidation of ferrous ion, mineral solubilization can be accomplished. Other than *Thiobacillus ferrooxidans*, the organism for microbial leaching that is mostly studied; iron and sulfur oxidizing archaea/bacteria are the probable candidates for metal bioleaching at low-pH and high-temperature conditions. Some moderately thermophilic (acidophilic-chemolithotrophic) and heterotrophic bacteria were exploited for leaching of metals from scrap that comprises *Sulfobacillus thermosulfidooxidans* (Ilyas et al. 2007).

18.4.1.2 Biosorption

Biosorption is based on the absorption and binding of solvable pollutants (ionized toxic metals) on the cellular surface. The ability of microbes, e.g., bacteria, algae, fungi, and plant biomass, to eradicate radionuclide and heavy metal ions or to encourage their conversion to less poisonous forms has captivated many researchers and biotechnologist's attention for many years. Thus, several thoughts for elimination of heavy metals from e-waste of polluted environment through microbes are being estimated, and some of them were taken to the industrial level (Volesky et al. 1993).

Biosorption mechanisms can be categorized according to the need of cell's metabolism that are known as metabolism dependent and independent according to the area from where the metal is found: from the removed solution that includes like cell surface sorption/precipitation extracellular accumulation/precipitation, and intracellular accumulation/precipitation (Muyzer and Stams 2008; Neethu et al.

Table 18.2 Use of several microorganisms for heavy metals removal from e-waste through bioleaching

Metals removed	Microorganisms	Temperature (°C)	pH
Copper (Cu)	*Acidithiobacillus ferrooxidans*	45	2–3
	Acidithiobacillus thiooxidans	45	2–3
	Aspergillus niger	30	3–4
	Penicillium simplicissimum	32	2–6
	Gallionella sp.	30	2–6
	Leptospirillum sp.	45	3
Zinc (Zn)	*Acidithiobacillus ferrooxidans*	45	2–3
	Acidithiobacillus thiooxidans	45	3–4
	Aspergillus niger	30	2–6
	Penicillium simplicissimum	32	2–6
Lead (Pb)	Strain of F3-02 *Acidithiobacillus ferrooxidans*	45	2–3
	Acidithiobacillus thiooxidans	45	3–4
	Aspergillus niger	30	2–6
	Penicillium simplicissimum	32	2–6
Aluminum (Al)	*Bacillus circulans* and *B. mucilaginosus*	35	4–5
	Acidithiobacillus thiooxidans	45	3–4
	A. ferrooxidans	45	2–3
	Aspergillus niger	30	2–6
	Penicillium simplicissimum	32	2–6
Nikel (Ni)	*Acidithiobacillus thiooxidans*	45	3–4
	A. ferrooxidans	45	2–3
	Aspergillus niger	30	2–6
	Penicillium simplicissimum	32	2–6
Gold (Au)	*Chromobacterium violaceum*	30–37	3.0
	Pseudomonas fluorescens	25	7–8
	Desulfovibrio desulfuricans	35–43	2.0
	Acidithiobacillus sp.	45	3–4
	Leptospirillum thiooxidans	45	2–3
	Ferromicrobium	45	2–3
	Acidiphilium	45	2–3
Silver (Ag)	*Acidithiobacillus* sp.	45–60	2–3
	Leptospirillum sp.	45	2–3
	Ferromicrobium	45	2–3
	Acidiphilium	45	2–3
Cadmium (Cd)	*Aspergillus niger*	30	2—6

Adapted from Pant et al. (2012)

2015). During metabolism-independent mechanism, metal uptake is based on physiochemical interactions present between the functional groups existing on the bacterial cell surface and metal. As it is not based on cell's metabolism, it depends on chemical sorption, physical adsorption, and ion exchange. Microbial cell wall primarily comprises of carbohydrates, lipids, and proteins that have plentiful metal

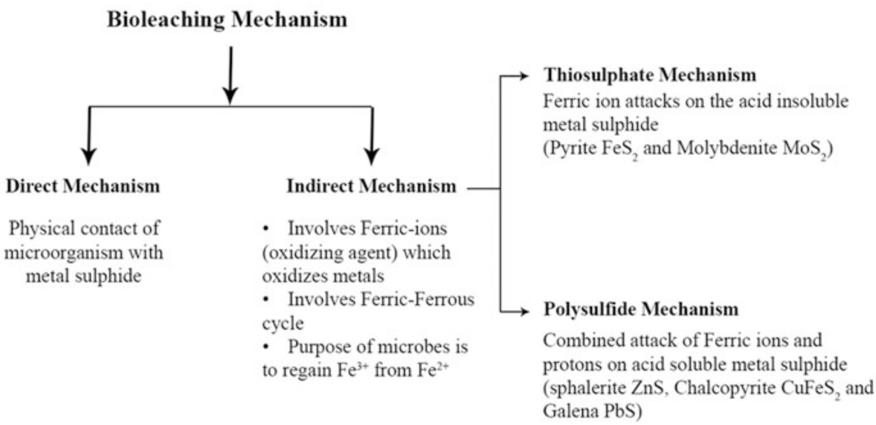

Fig. 18.2 The mechanisms of bioleaching process (Adapted from Pant et al. 2012)

absorption groups such as phosphate, sulfate, amino, and carboxyl groups (Ahalya et al. 2003). The cleansing mechanism of microbes can be classified into:

- Intracellular segregation.
- Exporting the toxic ion away from the cell by changing the membrane transport system that is present in early cell's accumulation.
- Reducing the cell's permeability.
- Extracellular segregation by definite mineral ion absorption. Extracellular decontamination involves the enzymatic transformation of more toxic cations or anions into less toxic form.

The different bacterial, algal, and fugal strains that are used for heavy metals removal are listed in Table 18.3.

The difference between microbially enhanced chemisorption of metals and adsorption is a reaction that takes place between the adsorbate and the surface. In this case, a sequence of reactions take place in which microorganisms first infiltrate a biomineral of non-specific metals (priming deposits) and then they use these priming deposits as nucleation focus for the consequent target metal's deposition (Tabak et al. 2005).

18.4.1.3 Bioaccumulation

Bioaccumulation is based on the absorption of pollutants within the organism, which are changed into a cell biomass inside the cellular organelle and concerted there; this method involves dynamic metabolism. For organic chemicals, sometimes they are catalyzed inside cell cytoplasm to other less toxic contaminants; but, instead, the toxic metals that go inside are sequestered (Hou et al. 2006; Prakash et al. 2012).

Table 18.3 Common species that are used and their biosorption capacity for heavy metal removal

Species	Microorganisms	Metal removed	Biosorption capacity (mg/g)
Bacterial species	*Enterobacter* sp. *J*	Copper (Cu)	32.12
	Arthrobacter sp.	Copper (Cu)	17.87
	Pseudomonas fluorescence	Chromium (Cr)	40.8
	Pseudomonas sp.	Chromium (Cr)	95
	Enterobacter sp. *J*	Cadmium (Cd)	46.2
	E. coli	Nickel (Ni)	6.9
	Pseudomonas fluorescence	Nickel (Ni)	40.8
	Pseudomonas putida	Zinc (Zn)	17.7
	Bacillus jeotgali	Zinc (Zn)	222.2
Fungal species	*Aspergillus niger*	Lead (Pb)	34.4
		Copper (Cu)	28.7
	Saccharomyces cerevisiae	Lead (Pb)	270
		mercury (Hg)	64.2
	Penicillium simplicissimum	Cadmium (Cd)	52.5
		Zinc (Zn)	65.6
	Penicillium chrysogenum	Nickel (Ni)	260
		Lead (Pb)	204
		Copper (Cu)	92
	Penicillium purpurogenum	Chromium vi (Cr)	36.5
Algal species	*Sargassum* sp.	Cadmium (Cd)	84.7
	Chlorella miniata	Chromium (Cr)	34.6
	Spirulina platensis	Copper (Cu)	67.93
	Spirogyra sp.	Lead (Pb)	140
	Sargassum muticum	Zinc (Zn)	34.1
	Ulva lactuca	Cadmium (Cd)	43.02

Adapted from Mustapha and Halimoon (2015)

Vibrio harveyi, a common inhabitant of the saline atmosphere, is testified to have the ability for cadmium bioaccumulation (Cd) up to 23.3 mg Cd^{2+} per g of gasping cells. The other strains that are being used for the bioaccumulation include *Bacillus circulans*, *Bacillus megaterium*, *Deinococcus radiodurans*, and *Micrococcus luteus* for the removal of chromium and uranium metals; and some fungal strains *Aspergillus niger* and *Monodictys pelagica* are reported for the bioaccumulation including chromium and lead removal from the electronic scrap (Patel and Kasture 2014).

18.4.1.4 Biotransformation

Biotransformation approaches have the potential to use the microorganism's natural metabolic capability to accumulate, convert, or destroy the toxic complexes including radionuclides, hydrocarbon compounds, pharmaceutical constituents, and noxious heavy metals. Biotransformation denotes the method in which a substance is transformed by chemical reactions from one chemical form to alternative chemical form. For noxious metals, the oxidation state is altered by the electron's addition and removal; hence, their chemical characteristics are also different (Karigar and Rao 2011).

Rhodobacter sphaeroides and *Rhodobium marinum* have the potential of eradicating toxic metals like zinc (Zn), copper (Cu), lead (Pb), and cadmium (Cd) from the polluted water through biotransformation. Two mechanisms for biotransformation are: (1) direct-enzymatic reduction mechanism, wherein the exterior of the cell multivalent metal ions is lessen by taking electrons from the enzymes, and (2) indirect reduction mechanism, where multivalent metals are reduced and immobilized by the aid of metal-reducing or sulfate-reducing microbes in sedimentary or subsurface environment (Tabak et al. 2005).

Polyaromatic hydrocarbons (PAHs) are abundant in environment and are of much ecological distress because of their perseverance, noxiousness, and mutagenicity in nature. Some new aquatic bacterial species such as *Lutibacterium anuloederans*, *Cycloclasticus spirillensus*, and *Neptunomonas naphthovorans* have also been employed in advanced PAH biodegradation methods in an aquatic environment (Chung and King 2001). Numerous categories of plastics including polyethylene, polystyrene, polyvinyl chloride, polyethylene terephthalate, and polypropylene are being used for packing, fishing, etc. in our surroundings that eventually contaminate our environment. Still, microbes have advanced the mechanism for the breakdown of plastic to harmless form. Recent discoveries proved that *Rhodococcus ruber* can reduce 8% dry weight of plastic in concerted liquid culture (in vitro) in just 30 days. In the same way, bacterial strains from genera *Psychrobacter*, *Moritella*, *Shewanella*, and *Pseudomonas* that are being secluded from Japan's deep seas have the ability to degrade the ε-caprolactone in a much effective manner (Kathiresan 2003).

18.4.1.5 Biomineralization

Biomineralization is a method through which living organisms can produce minerals. The prokaryote mineralization can be grouped into two classes: biological-induced mineralization (BIM) and biological-controlled mineralization (BCM). In the case of BCM, minerals are formed at a definite site inside or on the cell at specific conditions, but in (BIM), the minerals are synthesized extracellularly because of organism's metabolic potential. The extracellular formation of these minerals gives a concept to the scientific community to employ this ability of microorganisms for wastewater treatment purposes (Lowenstam and Weiner 1989; Lowenstam 1981). The use of bacterial-induced carbonate biomineral is becoming progressively prevalent every day; removal of calcium and heavy metals from wastewater, removal of radionucleotides, CO_2 sequestration, contaminant biodegradation, and to the remediation of construction materials.

Biomineralization of contaminant toxic metals and radionuclides into calcite happens as a result of competitive co-precipitation reaction where appropriate divalent cations are fused into the calcite structure.

$$^{90}\mathrm{Sr}^{2+} + \mathrm{OH}^{-} + \mathrm{HCO}^{-3} = \mathrm{SrCO}^{3}(\mathrm{s}) + \mathrm{H_2O}$$

These radionuclides and cations assimilate into the calcite lattice via exchange of calcium (Ca^{2+}) ions in the microenvironment of mineral precipitate, making a low strontium carbonate mineral that has poorer solubility (Fujita et al. 2000). Scaling of channels and reactors occurs due to higher concentration of calcium ions almost 500–1500 mg/L in the wastewater that results in larger calcium formation in the form of carbonates, phosphates, and gypsum. In his study, Hammes and Verstraete 2002 found the ability of eliminating calcium ions (Ca^{2+}) from industrial wastewaters through microbial-induced calcite precipitation (MICP) method (Kumari et al. 2015). Almost 90% calcium ions (Ca^{2+}) was effectively detached from the inspected wastewater by the addition of low urea concentration (0–16 g/L). Likewise, Okwadha and Li (2011) described the capability of calcium for polychlorinated biphenyls (PCB) treatment and urea ureolytic *S. pasteurii* cultures. Bacterial strains like *Cupriavidus metallidurans*, *Bacillus fusiformis*, and *Sporosarcina ginsengisoli* are able to remove cadmium, arsenic, and lead, while fungal strain (*Aspergillus flavus*) can remove lead from e-waste through biomineralization (Patel and Kasture 2014).

18.4.2 Recommended EWM for Air Quality

The main factor in exposure to toxic chemicals during recycling and disposal is taking services of unskilled workers. First and foremost, remedial measure would be to recognize recycling as a formal industry and to enforce establishment of safe and state-of-the-art facilities for recycling and disposal of e-waste. Technical training courses need to be developed for skill development in this sector. Only trained workers should be engaged in recycling sites. There is also essential to improve the technology for recycling and to train the workers in safe extraction, recycling, and disposal systems. Adsorption of metal through adsorbents particularly alumina may be adopted for adsorption of metal fumes (Saini et al. 2017) which could otherwise be emitted into the atmosphere. For disposal of compact fluorescent lamps (CFLs), CFLs should be crushed in closed crushing units to separate and capture mercury in collection unit. This process will help prevent emissions of mercury fumes into atmosphere. Similar metal extraction processes may be opted for safe recycling process.

An example of good governance may be taken from Nigeria wherein the country imposed import duty on imported electronic waste. Recently, Thailand has executed an embargo on import of e-waste for recycling as the country is concerned about the dangers to public health and environment. Such initiatives bring awareness to public about the hazards of recycling which are usually overlooked for economic benefit. Despite being signatory to the Basel Convention, the Government of Thailand took the right action considering lack of safe disposal facilities and practices.

18.5 International Regulations

To regularize the transboundary movement of harmful waste, "Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal" was implemented in 1989 and came into force in 1992. There are 178 participants to the Basel Convention, including almost every country in East Asia and the Pacific. The purpose of the Basel Convention was to provide the importing countries with regulating mechanism of "notice and consent." The purpose of the Basel Convention was to guard human health and the ecosystem from the hazards rising due to recycling and removal of harmful waste. E-waste is also regulated under the Basel Convention. Currently, used products are also exported to developing countries for refurbishment and repair under the Basel Convention. The United States holds an opposing position with the justification that transboundary movement of used electronic products does not establish such material to be waste and hence such items may not fall within the purview of the Basel Convention.

PCBs, commercial penta-bromo-diphenyl ether (c-Penta BDE), constituents of hexabromobiphenyl (HBB), and industrial octa-bromo-diphenyl ether (c-Octa BDE) have been constrained under Stockholm Convention on Persistent Organic Pollutants (POPs) because of their resistance to degradation and bioaccumulation potential (Stockholm Convention 2009a, b) prohibiting their manufacture, consumption, import, and export. However, PBDEs regulated under Stockholm Convention have an exemption of recycling and reuse. Permission to be recycled and reused is not justified due to possible risk of exposure (Stockholm Convention 2010a, b).

Other compounds of major concern are refrigerants released from dumping of refrigerators and air conditioners. These refrigerants include ozone-depleting substances (ODS) and greenhouse gases like HFCs. International trade of ODS is regulated under the Montreal Protocol on Constituents that diminish the ozone layer, whereas HFCs are covered under the Kigali Amendment to the Montreal Protocol and the Kyoto Protocol to the UN Framework Convention on Climate Change. The Kigali Amendment to the Montreal Protocol was implemented on October 15, 2016, in Kigali, Rwanda. It demands high-income developed countries to pledge down hydrofluorocarbons (HFCs), a replacement of CFCs, by 2019 year and low-income developing countries to initiate in the future. The Kigali

Amendment came into power since the higher global warming capabilities of HFCs. Phasing down of HFCs under the Montreal Protocol is projected to evade up to 0.5°C temperature by end of the era.

18.6 EWM Methods Adopted in Developing Countries and Their Impacts

Transboundary movement of almost 80% of the electronic waste from high-income developed countries to low-income developing world has led to increase in the exposure risk of hazardous and toxic chemicals. Developing countries accepting e-waste for recycling include China, India, Pakistan, Thailand, Ghana, Nigeria, Vietnam, and the Philippines. Currently, these countries have very less safe and formal recycling and disposal facilities for electronic waste. Recycling is poorly regulated and is carried out mostly in scrapyards with no occupational, health, and safety measures. In these facilities, hazardous substances are sometimes exploded due to manhandling by non-skilled workers. Increasing burden of electronic waste, and its unsuitable handling and removal through open combustion or in landfills, affects the environment and public health significantly. It also poses some challenges to sustainable development. Electronic waste has raised up some serious problems due to the core constituents present in these which are harmful and are non-biodegradable. According to UNU & ITU report, entire countries in the world collectively produced an overwhelming 44.7 million metric tons (Mt) of electronic waste annually in 2016 or an equivalent of 6.1 kilogram per resident (kg/resident), comparable to the 5.8 kg/resident produced in 2014, that is almost equal to 4500 Eiffel Towers every year. The quantity of e-waste is anticipated to increase to 52.2 million metric tons, or 6.8 kg/citizen, by 2021. 44.7 million metric tons (Mt), nearly 1.7 Mt are dumped as waste in highly developed countries and are possibly to be landfilled or burned. Only 8.9 Mt of electronic waste are said to be collected and recycled worldwide, which is equivalent to 20% of all the electronic waste produced. E-waste statistics are not appropriate only in terms of the ecological effect; there is also a significant economic factor to the discussion. The total worth of all electronic-waste raw materials is projected at nearly 55 billion euros in 2016, which is greater than the gross domestic product (GDP) in 2016 of some countries (Balde et al. 2017). The electronic-waste generation and its collection per continent are listed in Table 18.4.

The electronics business is one where subcontracting of mass-produced products is accompanied by major other companies. Mostly genuine equipment producers have fragmented their straight industrial chains and labor-intensive tasks. Most of labor-intensive manufacturing activities have been migrating to low-income or developing countries, where labor cost is lesser (Plepys 2002).

Table 18.4 E-waste generation per continent and their collection

Regions	Countries in region	Population in region (million)	E-waste generation in region (Mt)	E-waste generation per citizen (kg/citizen)	Documented, collection, and recycled (Mt)	Collection rate (%) in region
Asia	49	4364	18.2	4.2	2.7	15
Europe	40	738	12.3	16.6	4.3	35
America	35	977	11.3	11.6	1.9	17
Africa	53	1174	2.2	1.9	0.004	0
Oceania	13	39	0.7	17.3	0.04	6

Adapted from UNU and ITU (2017)

18.6.1 Landfill Disposal

Regardless of the recent universal change toward zero wastes, the quantity of landfills keeps on multiplying in low-income developing countries. In landfilling, dugouts are built on the plane exteriors, soil is mined from the dugouts, and waste material is concealed in it, which is enclosed by a dense layer of soil. Current practices such as safe landfill have been given with some conveniences like impermeable lining constructed by clay or plastic, leachate collection sink that gathers and handover the further leachate to wastewater treatment plants. Townsend et al. (2004) confirmed 12 diverse categories of electronic devices such as monitors, CPUs, laptops, VCRs, TV sets, remote controls, cellular phones, printers, etc. In most of the cases during experimentation, lead (Pb) concentration level in the leachates exceeds the minimal limit of 5 mg/L, and each device leached lead (Pb) more than its minimal level in at least one assessment. The authors determined that these outcomes give enough evidences that electronic devices scrap that comprise any printer wiring boards or color CRT with lead bearing fuse have the harmful wastes for lead (Pb) metal (Townsend et al. 2004). Contaminants have the capacity to move through groundwater and soils inside and around landfill areas. Organic contaminant in landfill decays and infiltrates into the soil in the form of landfill leachate. Leachates can have higher concentrations of suspended and dissolved inorganic substances, organic materials, and toxic heavy metals. But, the concentration level of contaminated materials from leachate depends on the scrap properties and phases of waste breakdown in a landfill (Qasim and Chiang 1994; Kasassi et al. 2008).

18.6.2 Incineration

Incineration is a controlled and ample burning process, where the waste elements are burned in specifically intended incinerators at higher temperature almost at 900–10000 °C. The e-waste incineration advantages include the reduction of electronic-waste bulk and the consumption of the energy component of ignitable compounds. Secondly, through incineration many environmentally harmful organic materials are transformed into less harmful substances. Stewart and Lemieux performed tests on incineration of the PC's motherboards, keyboards, and cases mixtures by means of pilot-scale rotary kiln incinerator. The vent gas was investigated for volatile and semi-volatile organic compounds of partial burning, halogens, heavy metals, as well as PCDDs/Fs. The detected metal discharge was substantial and comprised of copper (Cu), cadmium (Cd), lead (Pb), mercury (Hg), and antimony (Funcke and Hemminghaus 1997; Stewart and Lemieux 2003). The shortcomings of incineration are the compound discharge to air, the evasion from vent of gas cleaning, and the high number of residues from combustion and gas cleaning. In countries such as Ghana, India, Indonesia, and China, where electronic waste is transported for recycling, there is no advancement of technology; therefore, e-waste scrap is burned in the open environment. All the highly noxious substances escape into the atmosphere. Hence, the inappropriate electronic-waste recycling, specifically e-waste incineration, poses a severe risk to human beings as well as to the whole ecosystem (Pramila et al. 2012).

18.6.3 Recycling

Recycling comprises disassembling, i.e., exclusion of diverse parts of electronic waste covering harmful materials, such as PCB and mercury (Hg), plastic and printed circuit board separation, elimination of CRT, and sequestration of non-ferrous and ferrous metals. Enormous amount of e-waste is now being transported around the globe for recycling in low-income/developing countries by labor-intensive process in the yards of residential areas. E-waste recycling is significant because of the rich sources of raw material, removal of toxic substances, and solid waste management (Asante et al. 2012). The process of e-waste recycling is illustrated in Fig. 18.3.

Although the recycling process is a developing and evolving industry, its hazardous effects are being neglected so far. The extent of harms posed to labors and the atmosphere, thus, differs significantly depending on the particulars of the separate facility maneuvers. The risk related to dismantling phase is the unintentional releases and leakages of harmful materials. For example, mercury (Hg) inside light sources such as fluorescent tubes of photocopiers, scanners, etc. as well as switches could be discharged into the surroundings of a recycling area on rupturing of the shell (Aucott et al. 2003).

In a US electronics recycling facility, evaluation of air quality in the area of electronic-waste shredders has revealed lead (Pb) and cadmium (Cd) concentration level as high as 0.27 and 1.4 lg/m^3, respectively. This outcome shows that there were workplace pollution and a likelihood of constant exposure of labors to these noxious metals (Peters-Michaud et al. 2003). Wang and Guo (2006) measured the considerable concentration level of lead (Pb) in external water downstream of the recycling facility in Guiyu, China. The level of lead (Pb) concentration was high as 0.4 mg/L,

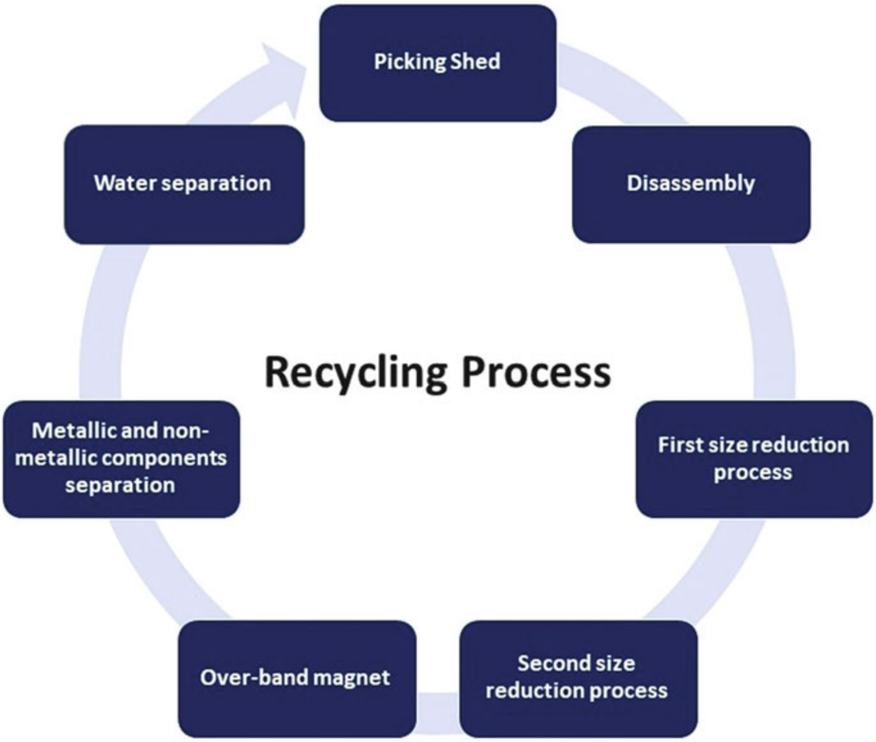

Fig. 18.3 Different steps involved in e-waste recycling process

that is, almost eight times greater than the China drinking water standard. The results from few other studies also validate the drastic pollution of the atmospheric air from brominated and chlorinated substances and toxic metals near e-waste recycling areas in Guiyu, China, and India (Li et al. 2007; Ha et al. 2009).

18.7 E-waste with Reference to Pakistani Perspectives

Most of the electronic waste from developed countries is transported to Pakistan. According to an estimate by the European Union, the e-waste will rise annually by 3–5%, while it also comprises of greater part of municipal waste. Karachi is the hub when it comes to dumping site of electronic waste in Pakistan. Lots of children are engaged in e-waste industry when it comes to reuse and recycling of e-waste products in Pakistan. Metals and plastics are taken out from electronic devices such as mobile phones, computers, televisions, etc. All the management of e-waste is done by adults and children with no personal protective equipment (PPE), but children are more vulnerable at the growing stage. In Layari, the e-waste chemicals

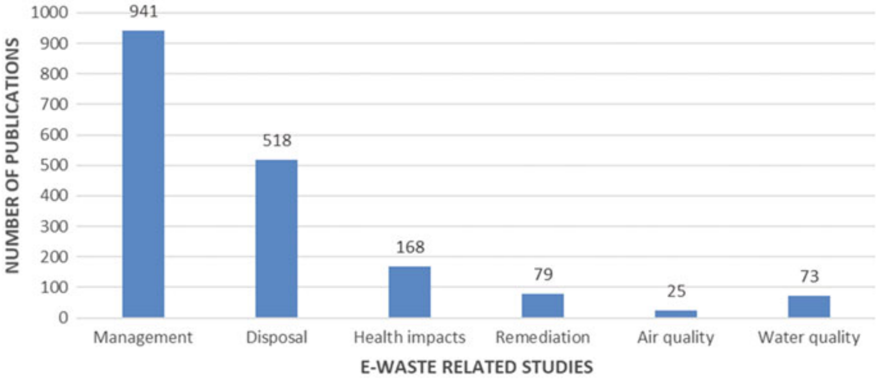

Fig. 18.4 Studies conducted on e-waste during the period between 2000 and mid-2018

from the dumping site seep into the nearby river that turns the river water black (Hai 2013). The same practice has been seen in other cities like Lahore, Rawalpindi, Peshawar, etc. Safe ways for disposal, proper regulations at the government level, and their implementation are recommended in already-published studies to circumvent health-related problems in the country (Iqbal et al. 2015; Sajid et al. 2018; Umair 2015).

18.7.1 E-waste-Related Studies

Studies conducted on different thematic areas of electronic waste such as e-waste management, its disposal, health impacts, and e-waste with reference to air and water quality during the past 17.5 years were analyzed (Fig. 18.4). The information of the total number of studies conducted have been collected from ISI Web Of Knowledge (http://www.digitallibrary.edu.pk/isi.html). The 941 studies were on management of e-waste, 518 studies on disposal of e-waste, 168 studies on health impacts of e-waste, and 79 studies on remediation of e-waste, while 25 and 73 studies were published on e-waste-related air and water quality, respectively, during 2000 to mid-2018. This indicates the pollution related to remediation and e-waste regarding air and water quality have been paid less attention as compared to management, disposal, and health impacts.

18.8 Conclusion

E-waste management and disposal is an important area of research especially with reference to developing countries. In Pakistan, e-waste is not considered as separate surplus as per its risks and hazards involved and combined with solid waste.

Children are more vulnerable to e-waste as they collect e-waste without using PPE. Lack of awareness can cause serious health issues, and there is terrible need to create awareness among the general public regarding risks of e-wastes. Safe disposal of e-waste is suggested along with the solid waste, and sound policies regarding EWM and their implementation is important. More work is required to protect the environment especially in the area of water and air quality; as indicated, less work has been done in both these areas.

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