Metallurgical processes unveil the unexplored "sleeping mines" e- waste: a review

Pooja Thakur[1] · Sudhir Kumar[1]

Abstract
The aim of this review paper is to critically analyze the existing studies on waste electric and electronic equipment (WEEE), which is one of the most increasing solid waste streams. This complex solid waste stream has pushed many scientific communities to develop novel technologies with minimum ecological disturbance. Noteworthy amount of valuable metals makes e-waste to a core of "urban mining"; therefore, it warrants special attention. Present study is focused on all the basic conceptual knowledge of WEEE ranging from compositional analysis, global statistics of e-waste generation, and metallurgical processes applied for metals extraction from e-waste. This review critically analyses the existing studies to emphasize on the heterogeneity nature of e-waste, which has not been focused much in any of the existing review articles. Comprehensive analysis of conventional approaches such as pyrometallurgy and hydrometallurgy reveals that high costs and secondary pollution possibilities limit the industrial feasibilies of these processes. Therefore biohydrometallurgy, a green technology, has been attracting researchers to focus on this novel technique to implement it for metal extraction from WEEE.

Keywords E-waste · Urban-mining · Sleeping mines · Pyrometallurgy · Hydrometallurgy · Biohydrometallurgy

Introduction

In today's scenario, revolutionary development has connected everyone and created a digital economy. Everyday electronic companies are introducing products with new features and services at cheaper rates, which are increasing the demand for these electronic equipment. In parallel, this increased demand for electronic equipment is generating a high amount of waste electronic products considered as e-waste or WEEE, which is a prominent solid waste stream (Chauhan et al. 2018). Increased number of users, economic development, and innovation in technology are few factors responsible for this growing amount of e-waste. Numerous studies have been reviewed like consumption and usage of e-waste, market and distribution analysis, material flow analysis, and export analysis to estimate the e-waste. There could be a considerable variation in reports due to assumptions and strategies applied in different studies, making the quantification of WEEE generation difficult. These challenges have prompted researchers to regulate the increasing e-waste, as these accumulated wastes liberate the alternative pollutants and heavy metals (Perkins et al. 2014; Pant et al. 2012). There are many conventional as well as advanced strategies applied for e-waste treatment. Although, the traditional procedures are effective for recovering metals, yet need is felt for the development of a novel approach to create a standard system to treat e-waste and retrieve metals. Comprehended information is available regarding the existing approaches like hydrometallurgical and pyrometallurgical technologies for WEEE recovery. This review aims to highlight the international and national scenario of e-waste production, heterogeneity with metals concentration, which is not focused yet in any of the studies, discussion about the different techniques being used and improvements in biohydrometallurgical process.

Composition of e-waste

The equipment which works on the electromagnetic field or electric current is classified as electrical and electronic

✉ Sudhir Kumar
  sudhir.syal@juit.ac.in

1   Department of Biotechnology and Bioinformatics, Jaypee University of Information Technology, Waknaghat, Solan, Himachal Pradesh 173234, India

equipment (EEE). These equipment generate and measure the electromagnetic field or current (Perkins et al. 2014). Regular upgradation in all the electric and electronic equipment leads to generate tremendous amount of outdated products as e-waste. WEEE consists of various toxic substances, with three main categories, i.e., ceramics, metals, and organic materials (Xia et al. 2018). PCB (printed circuit board) is considered as principal constituent of major electronic products, made up of 305 types of plastics, 30% refractory oxides together with enol, and 40% metals (in which Cu holds 10–30%) (Jagannath et al. 2017). Therefore, WEEE is claimed to have a complex, diverse, and heterogeneous composition comprising iron steel (50%), non-ferrous metal (13%), plastics (21%), and other constituents (16%) such as ceramics, glass, and rubber (Anshu and Hait 2017; Uddin 2012). Copper, zinc, and nickel are classified as non-ferrous metals which are abundantly found in WEEE. Table 1 represents the major metallic constituents along with their sources in electric and electronic equipment. Polycyclic aromatic hydrocarbons (PAH), polybrominated dibenzo-p-dioxin (PBDD), and polybrominated diphenyl ethers (PBDEs) are classified as plastic, whereas brominated flame retardants (BFR), dibenzofurans, dioxins, and glass fibers have been considered into organic materials; additionally, alkaline earth oxides, alumina, barium titanate, and silica have been categorized in ceramic group (Julander et al. 2014; Imran et al. 2017). The liberation of some hazardous metals like cadmium, beryllium, mercury, and chromium into the ecosystem is responsible for toxicity of WEEE (Anshu and Hait 2018). Seeing the complexity, heterogeneity, and harmful effects of e-waste, management, and resources conservation has become the utmost concern to avoid resulting pollution.

Global statistics of WEEE generation

Quantification of e-waste is the critical step to consider the challenges coupled with WEEE. Significant amount of data related to e-waste will help us in regulating illegal dumping and e-waste generation. According to a survey conducted by United Nation University (UNU), in 2016, worldwide e-waste quantity was 44.7 Mt which is anticipated to excel more than 52.2 Mt by 2021 with 4% annual extension rate (Wang et al. 2016). Only 20 % (8.9 Mt) of total waste is subjected for its collection and recycling purpose whereas 35.8 Mt (80%) is undocumented and dumped illegally into the landfills. High gross domestic product (GDP) of developed countries is responsible for higher e-waste production rate in term of kilogram (kg) per inhabitant as compared with developing countries. Top ten countries with highest e-waste contribution are listed in Table 2. In spite of low rate of e-waste generation per inhabitant (4.2 kg/inh), Asia was found to be top producer with total 18.2 Mt (Jagannath et al. 2017; Wang et al. 2016). From Asian continent, China contributed the highest amount (7.2 Mt) followed by Japan and India with 2.1 and 2 Mt, respectively. Despite of greatest collection rate (35 %), Europe listed second rank among the continents with 12.3 Mt in parallel to 16.6 kg/inh. According to the global e-waste Monitor 2017, in Europe, Germany contributed highest quantity (1.9 Mt), followed by Great Britain and Russia 1.6 Mt and 1.4 Mt, respectively. Americas produce total 11.3 Mt of e-waste with 6.3 Mt contributions from United State of America (USA) itself. Brazil ranked second, with 1.5 Mt, followed by Mexico, with 1 Mt (Anshu and Hait 2017). Africa holds last rank where Egypt contributes 0.5 Mt and 0.3 Mt contributions from South Africa and Algeria. Oceania continent ranked last for total e-waste generation (0.7 Mt) with 6 % collection rate, but considered greatest producer in terms to per inhabitant (17.3 kg/inh) (Awasthi et al. 2016a). The rising rate of this municipal solid waste stream have been alarmed many countries for adopting e-waste legislation. Currently, national e-waste management policies and legislation covered 66% of the world population, which has been increased from 44% since 2014. Being highest inhabitant countries of Asia, 72% population of China and India has enacted strict e-waste legislation. China has showed

Table 1 Constituents of WEEE and their source

Constituents	Sources
Base metals	Printed circuit boards
Precious metals	Mobile chip resistors, printed circuit boards
Nickel (Ni)	Nickel-cadmium chargeable batteries
Lithium (Li)	Lithium-ions batteries
Barium phosphorus and heavy metals	CRTs
Chromium (Cr)	Plastic computer housing, CRTs and batteries
Brominated flame retardants (BFR)	Electronic equipment and circuit boards
Plastic and PVC	Cables and computer body
Mercury (Hg)	Switches and circuit boards
Cadmium (CD)	Chip resistors and semiconductors
Arsenic (As)	CRTs, LCD screen, printed circuit boards

Table 2 List of countries contributed highest amount of e-waste in 2016

Sr. No	Countries	E-waste generation million metric ton/year	E-waste generation Kg/inhabitant	Population (millions)
1	China	7.2	5.2	1378
2	USA	6.3	19.4	323,9
3	Japan	2.1	16.9	126
4	India	2	1.5	1309
5	Germany	1.9	22.8	82.5
6	UK	1.6	24.9	65.5
7	Brazil	1.5	7.4	206
8	Russia	1.4	9.7	143
9	France	1.3	21.3	64.5
10	Indonesia	1.2	4.9	258.8

strong responsibility also in formal recycling, and metals recovery from e-waste Awasthi and Li 2017. In 2011, National Television and Computer Recycling Scheme was implemented by Australian government, which resulted into the recycling of 7.5 % of total generated e-waste. The issues of poor e-waste management facilities of the low economic countries require urgent attention. Figure 1 represents the global e-waste generation along with recycling data for different continents.

Urban mining—an economic perspective

In 2016, the net worth of e-waste was estimated to be $ 61.05 billion, which is higher than the GDP of most developing countries. Moreover, e-waste is the reservoir of many valuable

metals having concentrations 40 to 50 times higher than natural deposits, which makes this waste to "sleeping mines" (Kumar et al. 2018). More surprisingly, gold and silver are two precious metals consumed tremendously (i.e., 320 ton and 7500 ton, respectively) each year for production of new electronic products as reported by Environmental Protection Agency (EPA). Hence, about $ 21 billion worth precious metals are present in these devices. Altogether 60 different elements are found in the electronics devices, which can be recovered. E-waste generally contains high amounts of aluminum and iron along with plastic, which can be reused (Das and Ting 2017). UNU reported that e-waste globally contains secondary raw materials of worth approximately $ 60 billion as shown in Table 3, considering the significance of waste electronic products; there is a need for the establishment of a
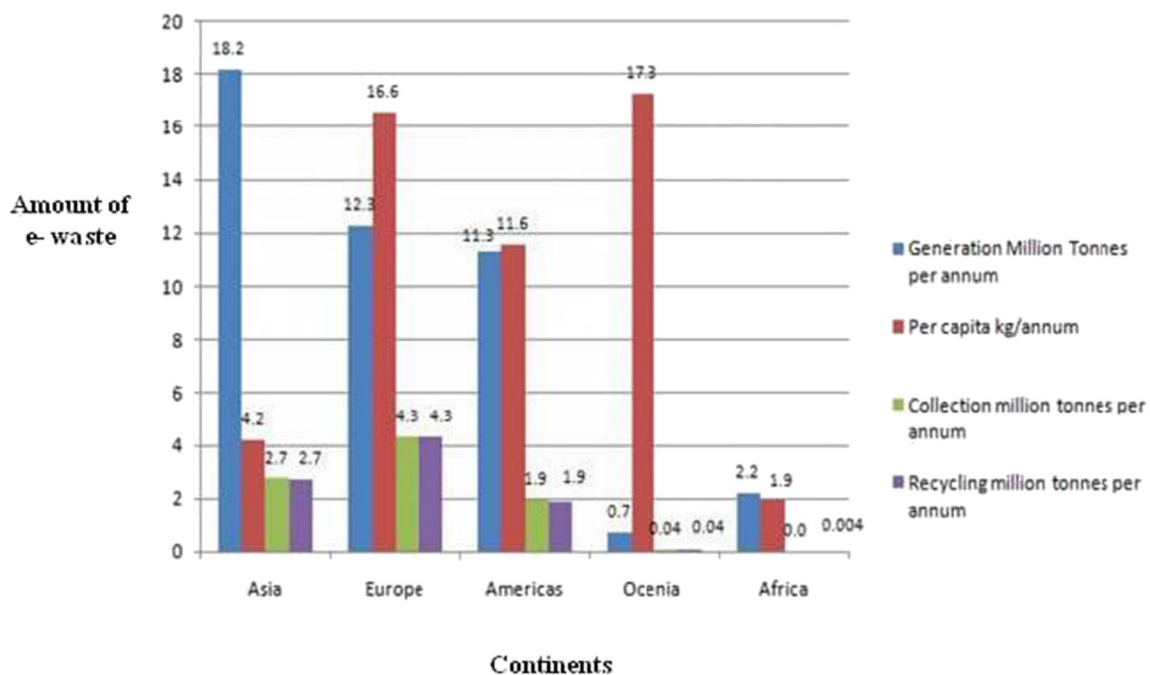

Fig. 1 Continents contributing total amount of e-waste along with collection and recycling rate

proper management system which allows the regulated recovery of valuable metals from dumped electronic equipment. EPA reports have stated that, by recycling 1 million cell phones alone, we can recover 10 tons copper, 0.01 tons of palladium, 0.275 tons of silver, and 0.025 tons of gold. Therefore, to utilize this chance, there is a need for framing new policies which aid in developing an infrastructure having advanced equipment capable of retrieving highly invaluable metals from e-waste.

Heterogeneity of e-waste

Heterogeneity of e-waste is the key challenge which prevents us to determine the precise amount of metals in same WEEE samples. PCBs (printed circuit boards) are considered to be the most vital component in most electronic products. As per the statistics provided by Ministry of Information Industry of China, PCBs production in 2010 was around 1.1×10^9 m^2 corresponding to 30% share in the global market (Chauhan et al. 2018). These facts impose threat of rapid increase in e-waste. Various studies have been conducted on PCBs to quantify different metal concentration in it. One-gram sample of waste PCB was assessed by Xiang et al. (2010) and found that PCB sample contains aluminum (26 mgg^{-1}), copper (231 mgg^{-1}), lead (29 mgg^{-1}), tin (19 mgg^{-1}), and zinc (17.5 mgg^{-1}). Pardhan and Kumar (2012) determined the metal composition of PCBs scrape. They found 152-mgg^{-1} copper, 46.3-mgg^{-1} aluminum, 32.5-mgg^{-1} iron, 29.3-mgg^{-1} lead, 17.5-mgg^{-1} nickel, 11.2-mgg^{-1} zinc, 0.58-mgg^{-1} silver, and 0.29-mgg^{-1} gold. Gu et al. (2017) analyzed PCBs of spent mobile phones with 203-mgg^{-1} copper, 48.39-mgg^{-1} nickel, 62.25-mgg^{-1} tin, and 1.11-mgg^{-1} gold. In 2018, Wu et al. (2018) found the presence of 0.85-mgg^{-1} aluminum, 65-mgg^{-1} copper, < 0.01-mgg^{-1} iron, 0.02-mgg^{-1} lead, 0.23-mgg^{-1} nickel, and < 0.01-mgg^{-1} zinc in 1-g PCB sample. Kumar et al. (2018) revealed the presence of 23.4-mgg^{-1} copper, 1.1-mgg^{-1} cobalt, 0.9-mgg^{-1} chromium, 22.2-mgg^{-1} of iron, 0.08-mgg^{-1} of gold, 2.0-mgg^{-1} of nickel, 0.4-mgg^{-1} of silver, and 0.7-mgg^{-1} of zinc in 1 g of PCB sample. Khatri

Table 3 Raw materials value of 44.7Mt WEEE generated in year 2016

Material	Kilotons (Kt)	Million €
Silver (Ag)	1.6	884
Aluminum (Al)	2472	3585
Gold (Al)	0.5	18,840
Copper (Au)	2164	9524
Iron (Fe)	16,283	3582
Palladium (Pd)	0.2	3369
Plastics	12,230	15,043

et al. (2018) analyzed the metallic composition of cell phones PCBs and found 275.5-mgg^{-1} copper, 63.7-mgg^{-1} iron, 17.9-mgg^{-1} zinc, 19.6-mgg^{-1} nickel along with other base metals and toxic metals whereas silver and gold like invaluable metals were found to be very less, i.e., 0.02 mgg^{-1} and 0.08 mgg^{-1}. Amount of precious metals in PCBs categorizes this e-waste into high, medium, and low grade scrape. Precious metals are significantly more in high class and medium class PCBs material whereas in low grade material precious metals content is very less. Xia et al. (2018) reported the presence of aluminum (0.88 mgg^{-1}), copper (2.49 mgg^{-1}), lead (0.78 mgg^{-1}), tin (0.1 mgg^{-1}), and zinc (0.35 mgg^{-1}) in PCBs without any precious metals in low-grade PCBs. Copper is found to be predominant metal along with other base metals in all PCBs sample, whereas precious metal concentration varies along with the size and processing of PCBs samples. These studies show and highlight the different metal concentration within the same PCBs e-waste. This heterogeneity trend is not limited to PCB samples, but it is same for other e-waste streams. This heterogeneous nature of electronic scrap limits recovery and recycling of metals (Joshi et al. 2017).

Recycling processes and their effects

There are two major sectors that are involved in WEEE management and recycling, i.e., "Formal" and "Informal". E-waste treatment is done with appropriated machinery and designed facilities in case of former process, which ensure the safe working environment. However, high cost of equipment and facilities restrict the usage of formal processing in many developing countries. Although, formal e-waste recycling units have proper facilities, yet the exposure of toxicants can affect the workers and surrounding environment (Cucchiella et al. 2015; Chancerel et al. 2009). Generally, informal recycling units are home-based, in which metals are recovered in unskilled and unscientific manner without proper equipment. In spite of high rule and regulations for e-waste, India and China have numerous informal e-waste recycling units. As in Delhi, about 25,000 people work in informal recycling unit to process approximately 25,000 tons of discarded electronic products per year (Pardhan and Kumar 2014). These informal recycling activities are not only contaminating environment but imposing the health risk on people. Various studies have comprehended information about the occurrence of heavy metals in and nearby recycling yards above the regulated limits fixed by EPA and WHO. Pardhan and Kumar (2014) claimed that soil of Mandoli area (New Delhi) is contaminated with 17.08-mgkg^{-1} arsenic (As), 1.29-mgkg^{-1} cadmium (Cd), 115.50-mgkg^{-1} copper (Cu), 2645.31-mgkg^{-1} lead (Pb) 12.67-mgkg^{-1} selenium (Se), and 776.84-mgkg^{-1} zinc (Zn). Various studies have also claimed that informal recycling through traditional techniques can lead

to different health issues like cancer and neurological disorders. Toxicants such as polychlorinated biphenyl (PCBs) are major components of e-waste, known to cause neuropsychological disorders such as cognition problems (Awasthi et al. 2016b; Alab et al. 2012; Annamalai 2015). Lead, a well-known toxic metal, also has imposed irreversible effect on nervous system causing anemia, behavioral change, brain damage, kidney failure, learning disruption, and miscarriages. Likely, cadmium (Cd) accumulation also leads to renal failure and osteoporosis. Even chromium (Cr) and mercury (Hg), used in batteries, printed wiring boards, relay, and switches, are associated with asthmatic bronchitis, convulsions, lung cancer, and skin damage as enlisted in Table 4 (Chatterjee and Abraham 2017; Awasthi et al. 2016a, b). Julander et al. (2014) investigated the soil of formal recycling units at Philippines and showed the abundance of Cu and other hazardous metals like Cd and Pb. These evidences possess great occupational threat on the workers occupied in formal recycling units and even to the environment. Thus, there is need of proper safety management to avoid harmful effects of WEEE on human as well as on the atmosphere.

Approaches employed to transform waste into wealth

E-waste is the core of urban mining with much higher copper (Cu) and gold (Au) content compared with natural mines. So it will be worthy to transform this waste into wealth by recovering valuable metals and conserving natural resources. Some studies reported that approximately 17,000 tons of CO_2 is emitted during production of one ton of gold through natural mines, whereas ~ 10,000 and ~ 14,000 tons of CO_2 is estimated for collection of palladium (Pd) and platinum (Pt), respectively (Chauhan et al. 2018). Hence, WEEE treatment for metals retrieval would be beneficial from both ecological as well as economic perspective. As no single approach is found

to be satisfactory for the complete recovery process, therefore, various stages such as mechanical treatment, segregation, and metallurgical treatments are applied to develop a collective process. There are various methods as shown in Fig. 2, used to process WEEE for metals extraction.

Mechanical method

Prior to metals recovery, physical processes are applied for dismantling and segregation of WEEE. Selective or simultaneous are the two ways to perform disassembling. The selective dismantling is selected for recycled oriented operations. In the simultaneous approach, all components are removed together by heating in furnace at high temperatures. In spite of high efficiency rate, risk of components destruction, additional sorting process and high operation cost limits the use of simultaneous disassembling process (Chauhan et al. 2018). Low speed high torque shear shredder is one of the instruments, applied for primary crushing to reduce the size of WEEE. Ball milling and disc milling are two other methods that have been accounted for the pulverization of WEEE (Ghosh et al. 2015; Yoo et al. 2009). Loss of precious metals, release of dust containing hazardous metals, brominated flame retardant (BFRs), and dioxins are the problems associated with shredding process. After the shredding, particle fractions are forced through gravity-based separation system, which separate out metallic and nonmetallic components based on their magnetic and electrostatic property(Joda and Raschi 2012) . Due to difference in the magnetic properties of ferromagnetic metals, magnetic separators are predominantly used to separate ferromagnetic metals from nonferrous metals (Chauhan et al. 2018). Ghosh et al. (2015) reported the mineralogical analysis of shredded dust produced during mechanical processing of PCBs and indicated the consistence of 73.1% organic matter, 4.55% iron, 4.65% aluminum, 1.06% lead, and 2.67% copper. So there is need of good collection systems in order to prevent dust exposure and loss of metals.

Table 4 Health effects of some hazardous metals present in WEEE

| Hazardous metals	Sources	Effect on human health
Lead (Pb)	Computer monitors, printed circuit boards	Cause damage to central nervous system, kidney, blood system, and reproductive system
Cadmium (Cd)	Chip resistors, semiconductors	Accumulated in the liver, kidney, pancreas, and thyroid
Mercury (Hg)	Thermostats, switches, mobile phones, batteries	Damage central nervous system as well as fetus
Chromium (Cr)	Corrosion protector of galvanized steel plates	Damage DNA, skin sensitization and kidney damage
Barium (Ba)	Protector to radiations	Brain swelling, muscles weakness, damage to heart, liver, and spleen
Berrilium (Be)	Mother board and finger clips	Cause lung cancer and skin disease
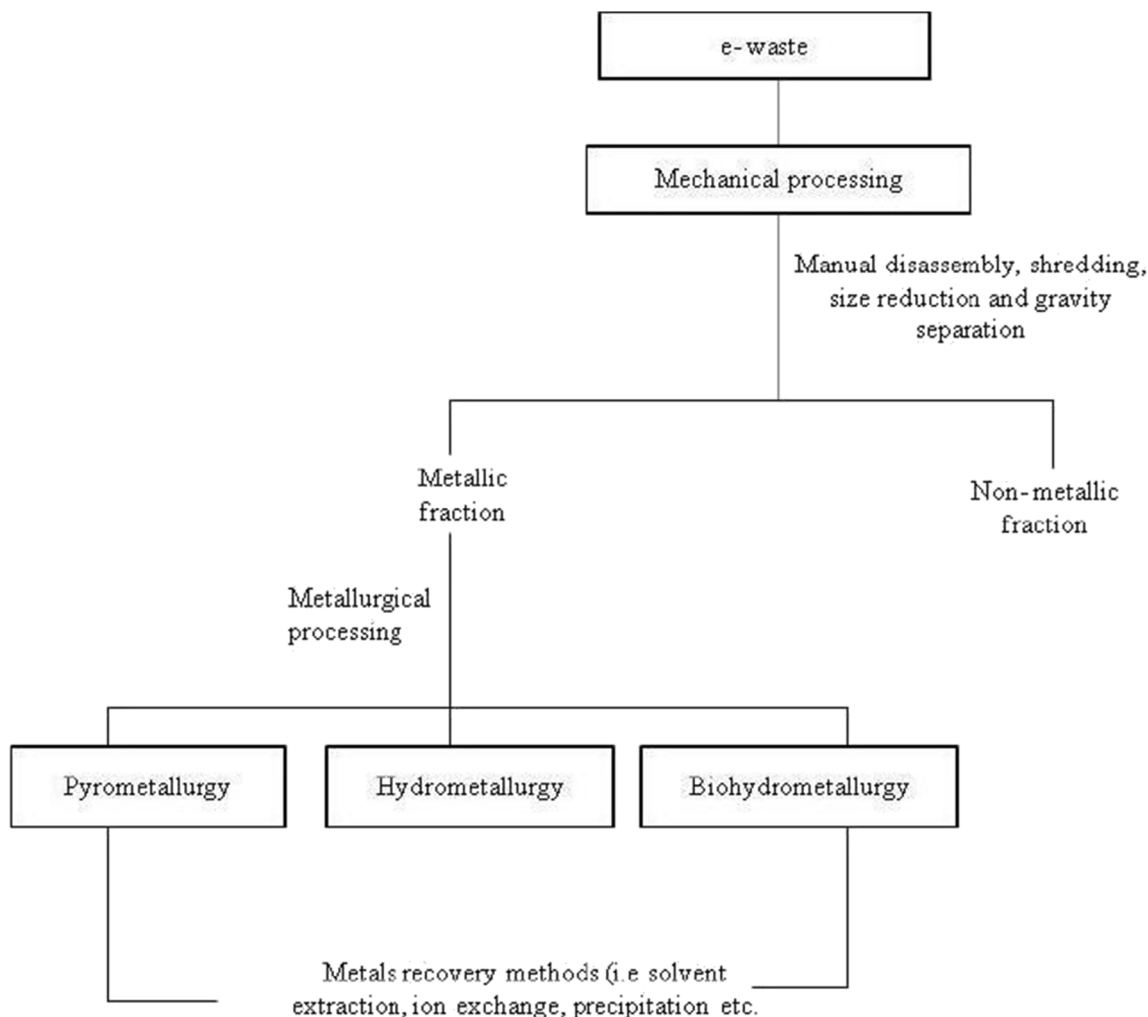
Fig. 2 Processes applied for metals extraction from WEEE

Yoo et al. (2009) processed PCBs through gravity separation method and segregated different particle fractions with 83% Ni and Fe and 92% Cu through two phase magnetic separation process. Separation techniques based on the electric conductivity difference are also predominantly applied to segregate WEEE as electric conductivity of different metallic constituents is the major property.

Metallurgical methods

Metals recovery from WEEE is a significant aspect in terms of ecological and economical prospective. Pyrometallurgy, hydrometallurgy, and biohydrometallurgy are important metallurgical processes applied for metal recovery from WEEE.

Pyrometallurgy process

Incineration, smelting, and roasting are most widely used pyrometallurgical methods. Aurubis smelter, Noranda smelter, Ronnskar smelter, and Umicore are some of the thermal
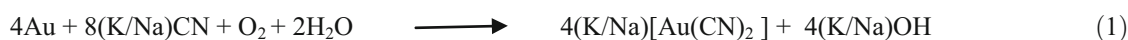
plants, available globally for formal processing through pyrometallurgical approaches. During smelting process, WEEE with high copper concentration is melted at high temperature (i.e., 1250 °C), followed by a conversion process to obtain 99.1% pure copper (Cu) blisters. Several precious metals remains left over after the completion of this process, which can be recovered through different methods, such as electrorefining and electrowinning. Therefore smelting process is considered as one of the finest methods for pure metals recovery. Presence of alloys and pure metals mixture makes the upgradation of final metals a challenging task, and it requires more energy (Chauhan et al. 2015, Chauhan et al. 2018). Xie et al. (2009) recovered Cu and Fe through new pyrometallurgy processes supported with cleaner ultrasonic technique, this showed higher efficiency rate and less toxic by-products generation. Polybrominated dibenzodioxins (PBDDs), phenol, dibenzo-p-dioxin, biphenyl, anthracene, dibromobenzene, naphthalene, and polybrominated dibenzofurans (PBDFs), are some of the toxic compounds emitted through pyrometallurgical treatment, which are highly

hazardous and may lead to serious environmental issues (Tue et al. 2013). Toxic byproducts and complexity in pure metals recovery are some of the additional problems, which limit the use of pyrometallurgical methods (Kuyucak and Ata 2013).
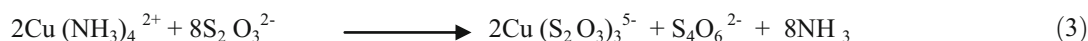
Hydrometallurgical process

Limitations of a pyrometallurgical process necessitate the use of hydrometallurgical methods. A release of less amount of toxic gases, less energy demand, easy accomplishment in the laboratory environment, and lower operating costs together with higher efficiency rate are some of the advantages, which attract the use of hydrometallurgical processes (Chauhan et al. 2015; Ni et al. 2013). Significant recovery of

base metals by hydrometallurgical treatment ensures fortification of some precious metals recovery and improves leaching efficiency rate through conventional methods such as ion-exchange and electrowinning (Coman et al. 2013). In hydrometallurgical method, cyanide and noncyanide chemical reagents act as strong lixiviants. Cyanide is a strong lixiviant, predominantly applied for precious metals recovery. At pH greater than 10.5, cyanide loss is limited as most of the free cyanide exists in ionic form (CN^-), so, at higher pH, cyanide is considered as an efficient and environmental friendly lixiviant (Kuyucak and Ata 2013; De et al. 2009). During cyanidation reaction, first cyanide is oxidized to cyanate which further reacts to form complex with metals (Chauhan et al. 2018).

$$4Au + 8(K/Na)CN + O_2 + 2H_2O \longrightarrow 4(K/Na)[Au(CN)_2] + 4(K/Na)OH \qquad (1)$$

$$\text{Overall: } 4Au + 8CN^- + O_2 + 2H_2O \longrightarrow 4Au(CN)_2^- + 4OH^- \qquad (2)$$

Temperature, pH, surface areas of WEEE sample, and presence of other ions are the predominant parameters which affect the rate of cyanidation process. Some of the researchers recommend pretreatment with acids like sulfuric acid or nitric acid along with some oxidizing agent to improve precious metals leaching by minimizing the simultaneous dissolution of copper metal. In spite of adequate information about the toxicity and safe handling of cyanide, environmental issues are still of serious concern and limit its use in an industrial practice (Chauhan

et al. 2015). Therefore, researchers have been moved towards less toxic chemical lixiviants such as thiourea, ferrous sulfate, and halide. Thiosulfate is another lixiviant primarily used for the solubilization of gold metal. Copper ion and ammonia along with thiosulfate solution improve gold metal recovery, and act as catalyst too (Aylmore and David 2001). The optimization of ammonia to thiosulfate ratio is considered as an important parameter for efficient recovery of metals. Equations (3) and (4) represent the chemical reaction for thiosulfate leaching.

$$2Cu(NH_3)_4^{2+} + 8S_2O_3^{2-} \longrightarrow 2Cu(S_2O_3)_3^{5-} + S_4O_6^{2-} + 8NH_3 \qquad (3)$$

$$2Cu(S_2O_3)_3^{5-} + 8NH_3 + 0.5O_2 + H_2O \longrightarrow 2Cu(NH_3)_4^{2+} + 6S_2O_3^{2-} + 2OH^- \qquad (4)$$

Xi et al. (2015) and Altansukh et al. (2016) recovered precious metals from mobile PCBs such as gold and silver by utilizing iodide as lixiviant. They claimed that iodine (I_2) to iodide (I^-) ratio affects the leaching efficiency. Low iodine concentration leads to less iodide formation and weak metal complexation ability, thus, precipitation of metal iodide complex takes place. Whereas higher iodine (I_2) concentration, simultaneously forms complex with base metals and create hindrance for precious metals leaching.

Hydrochloric acid (HCl), sulfuric acid (H_2SO_4), and mixture of sulfuric and nitric acids (HNO_3) are some of

the strong inorganic acids which have also been employed as lixiviant for metals dissolution. Behnamfard et al. (2013) utilized sulfuric acid with hydrogen peroxide for copper leaching from waste PCBs. Then followed the treatment with thiourea reagent along with ferric ion, and resulting into high gold and silver recovery (85.76%, 71.36%, respectively). Use of strong chemical reagents may result into release of large amounts of toxic byproducts associated with risk of environmental impact and hence reduce the applicability of hydrometallurgy.(Shah et al. 2014)

Biohydrometallurgical process

Biometallurgy or biohydrometallurgy is an ecofriendly, economical way of e-waste treatment. Biomining, bioextraction, biorecovery, and bioleaching are the alternative terms used for biohydrometallurgical process, which utilize metal solubilization potential of microorganisms from solid residues followed by recovery from solution. Brandl (2001) explained three principles of bioleaching process (1) acidolysis, (2) complexolysis, and (3) oxidoreduction reaction. During the last few decades, researchers have shown keen interest towards the exploration and characterization of microorganisms which shows natural mechanism for mineral leaching in natural environment. Table 5 enlisted microorganisms which have been used for bioleaching. Many studies reported that moderate thermophiles exhibit higher bioleaching potential than mesophilic and extreme thermophiles, therefore many *Thiobacilli* bacteria and thermophilic fungi (e.g., *A. niger* and *P. simplicissimum*) have been used extensively to retrieve metals from e-waste or low grade metal reservoirs (Brandl et al. 2001; Jadhav et al. 2016).

Chemolithoautotrophic bacteria such as *Acidithiobacillus ferrooxidans* and *Acidithiobacillus thiooxidans* has been the most extensively used microorganisms, which have strong affinity to solubilize base metals (Cu, Ni, Al) (Brandl et al. 2001; Valix and Hong 2014). In 2013, Hu et al. involved bioinformatics approach to understand the metal resistance mechanism of *A. ferrooxidans.* They assessed differential gene expression of copper resistant gene *afe_*1073 in *A. ferrooxidans* DY26 and *A. ferrooxidans* DC strains through reverse transcription polymerase chain reaction followed by bioinformatics analysis of its P1b1-ATPase protein. They obtained lesser gene expression in strain DY26 than strain DC, although strain DY26 exhibited higher toxicity tolerance at same copper concentration. Due to differential expression of afe_1073, the transmembrane protein P1b1-ATPase played better role in pumping out Cu^{2+} ions from the cell and could reduce the harm of metal at lower afe_1073 expression. Further bioinformatics approach was utilized to predict the gene function regulation by quorum sensing involved in cell and substrate attachment. Banderas and Guiliani (2013) used Hidden Markov Models to predict the palindromic and nonpalindromic region used for binding sites. They identified 75 target genes out of which 34 showed high confidence levels. They also confirmed the presence of afeR-1073 gene, directly involved in polysaccharide production and enhance attachment of cell with substrate during bioleaching reaction. Other than acidophilic, cyanogens such as *C. violaceum* and *P. aeruginosa* have also been explored for the solubilization of precious metals (Au, Ag) (Ilyas et al. 2013). In 2001, Brandl et al. exploited the potential of acidophilic bacteria (*A. thiooxidans*, *A. ferrooxidans*) and fungi (*A. niger*, *P. simplicissimum*) to mobilize metals from e-waste. They obtained 65 % solubilization of Cu and Sn and 95% of Al, Ni, Pb, and Zn by fungal strains whereas bacterial strains solubilize 90 % Cu, Zn, Al, and Ni from 100 g/l e-waste sample. They suggested that high concentration of metals inhibit bacterial growth, therefore, reduce the production of lixiviants. Hence they proposed two step bioleaching processes where bacterial culture is first allowed to produce maximum lixiviant in the absence of e-waste followed by leaching process.

Table 5 Microorganisms capable to produce leaching lixiviants for metal extraction

Domain	Organism	Leaching agent
Archaea	*Sulfolobus* sp.	Ferric iron and sulfuric acid
	Acidianus sp.	Sulfuric acid
	Thermoplasma acidophilum	-
Bacteria	*Acetobacter methanolicus*	Gluconate
	Acidiphilum cryptum	Organic acid
	Bacillus sp.	-
	Bacillus megaterium	Citrate
	Chromobacterium violaceum	Cyanide
	Leptosprillum ferrooxidans	Ferric iron
	Pseudomonas putida	Citrate, gluconate
	Thiobacillus sp.	Ferric iron and sulfuric acid
Fungi	*Aspergillus* sp.	Citrate, oxalate
	Aspergillus niger	Oxalate, citrate, malate, succinate
	Penicillium funiculosum	Citrate
	Penicillium simplicissimum	Oxalate, gluconate, citrate
Yeast	*Candida lipolytica*	-
	Saccharomyces cerevisiae	-

Thereafter, many researchers selected two step bioleaching to reduce toxic effect of higher pulp density, to enhance leaching rate researchers utilized bacterial consortium and investigated synergistic effect of bacterial consortium. In 2009, Xin et al. commenced the use of mixed acidophilic bacteria for solubilization of Co and Li from spent lithium-ion batteries. Their results indicated that maximum Li solubilization occurred at lowest pH with sulfur as energy source whereas Co solubilization was influenced by higher pH medium supplemented with FeS_2 + S as energy source. Xiang et al. (2010) used bacterial consortium of genera *Acidithiobacillus*, *Gallionella*, and *Leptospirillum* and optimized the condition to favor best bacterial growth and maximum solubilization of Cu metal. They accomplished 95% Cu leaching with initial pH 1.5, 9-g/l Fe^{2+} concentration and 20-g/l pulp density. They demonstrated that leaching time can be reduced to 5 days by using consortium as compared to use of single culture (i.e., 12 days). They specified that two step bioleaching is necessary for bacterial growth and maximum lixiviant (Fe^{2+}) production; therefore, e-waste should be added to suitable time period. Pardhan and Kumar (2012) explored the bioleaching capability of cynogenic bacteria (*C. violaceum*, *P. aeruginosa*, and *P. fluorescens*) with a two-step bioleaching. They assessed the leaching rate of single as well as combined bacterial cultures of these three cyanide producing bacteria. They reported *C. violaceum* with highest leaching efficiency for maximum metals. 79.3% copper, 69.3% gold, 46.1% zinc, 9.8% iron, and 7.8% silver were recovered with *C. violaceum* among single cultures. Whereas, mixed culture of *P. aeruginosa* and *C. violaceum* showed maximum leaching for copper (83.46%) followed by gold (73.17%), zinc (49.11%), iron (13.98%), and silver (8.42%). Copper is the predominant metal present in e-waste, so its higher concentration causes hindrance for recovery of other valuable metals. Therefore some hybrid methods were developed to increase the bacterial leaching rate (Shah et al. 2015). Sahni et al. (2016) developed a chemobiohydrometallurgy hybrid technology to improve metal dissolution rate. They recovered 72% of copper through pretreatment of SIM waste with nitric acid; remaining copper was recovered from pretreated SIM waste by *C. violaceum* within 4 days. Khatri et al. (2018) and Ilyas et al. (2014) suggested ferrous sulfate and ferric sulfate as chemical lixiviant to improve the microbial leaching efficiency for base metals. Biohydrometallurgy process has also motivated researchers towards the genetic engineering approach to develop recombinant strains to enhance lixiviant production for improved bioleaching process. Natarajan et al. (2015) examined genetically engineered *C. violaceum* strains for gold recovery. They have demonstrated that cyanide production can be enhanced by engineering lixiviant metabolism in *C. violaceum*. Cyanide production increased up to 34.5 mg/L than the wild-type (20 mg/L) when additional hcnABC operon was induced. The genetically engineered strain showed 30% Au recovery at 0.5% w/v pulp

density, compared with 11% recovery by wild-type *C. violaceum*. In contribution of bioleaching process, Kumar et al. (2018) had seek out new isolate (*Pseudomonas balearica* SAE1) from e-waste recycling habituate, which shows higher toxicity tolerance (325.7 g/L of the e-waste pulp density) therefore exhibit increased leaching efficiency. For maximum metals solubilization, they optimized different parameters such as pulp density, glycine concentration, pH, and temperature. Their parameters optimization study resulted in 68.5 and 33.8% of Au and Ag solubilization, respectively, at pH 9.0, pulp density 10 g/L, temperature 30 °C, and a glycine concentration of 5 g/L. Biohydrometallurgical processes have found to be (advantageous) as directed towards the reduced environment footprint: cleaner alternative lixiviant, improve the methods for maximum lixiviant products, and decreased the production of hazardous material. Therefore Ilyas and Lee (2014) investigated the effect of different parameters such as aeration, O_2, CO_2 agitation, and pulp density and concentration of sulfur for *Sulfobacillus thermosulfidooxidans* in stirred tank reactors (2 L baffled glass reactor) to scale up the bioleaching process for industrial applicability. They obtained 91% Al, 95% Cu, 96% Zn, and 94% Ni in the presence of 2.5% sulfur containing medium enriched with 25% O_2+ 0.03% CO_2 at a 10% pulp density.

Sensitivity of microorganisms for different parameters, time requirement, selectivity, toxicity of elements, and possibility of contamination are some of the major issues which oppose commercial application of bioleaching process (Pollman et al. 2018). Sensitivity of microorganisms towards high toxic metal ions causes specificity; therefore, microorganisms cannot recover metals quantitatively. Toxicity of e-waste also has a direct influence on applied pulp density for large scale productivity. The exploration of indigenous bacteria habituating to high metals concentration as an alternative of recognized microbial strains from lab collections may overcome these limitations. Genetic manipulation of potential microorganisms and hybrid techniques may also empower biohydrometallurgical process. Thus, this technique requires interdisciplinary contribution from microbiology, biotechnology, engineering, and chemistry as well (Boxall et al. 2018). However, it is predictable that future development can overcome some of these limitations to progress biohydrometallurgical technique towards commercialization.

Comparative evaluation of metallurgical processes

The selection of an appropriate metallurgical technique is subjected to criteria such as capacity to metal extraction, workforce, time and energy requirement, and compatibility with environment. So, environmental consequence, resources involved, labor, expertise, and metal grade are some of the parameters must be considered prior to utilization of metallurgical technique (Chatterjee 2012). Pyrometallurgical treatment involves high-speed thermal
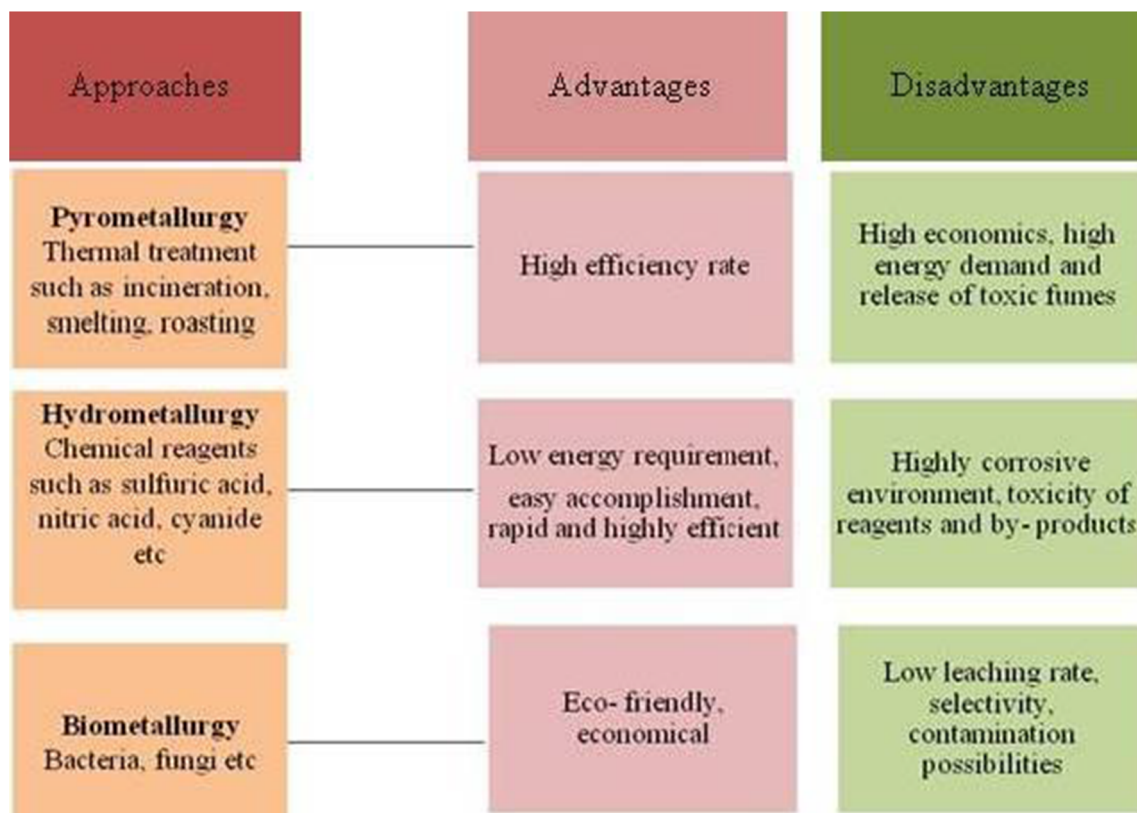
Fig. 3 Advantages and disadvantages of different metallurgical approaches

treatment which is overwhelming other techniques at industrial scale management. Due to high grade feed requirement, pyrometallurgy is not found to be suitable for low grade WEEE (Xia et al. 2018). Figure 3 represents the comparative assessment of all metallurgical processes. Loss of metals into slag or dust form and emission of poisonous gases are also a limitation accompanied with pyrometallurgy technique. Whereas hydrometallurgical process releases lesser poisonous gases in comparison with pyrometallurgy but high risks of acid solutions, and toxic fumes are major limitations associated with hydrometallurgy. Hydrometallurgy and biohydrometallurgy achieved high recuperation rate as compared with pyrometallurgy (Anshu and Hait 2017). Energy requirement, operation, maintenance cost, and environmental consequences are some other potential factors associated with pyrometallurgical and hydrometallurgical methods hence may not prove to be profitable. Biohydrometallurgy is green and economical alternate to the traditional metallurgical processes. In 2002, a US National Research Council committee states "the application of biohydrometallurgy as an important hydrometallurgical processing tool" (Rahman 2016). Therefore now, mining industries also recognize this technique as promising technology showing great potential for economic metals recovery from mineral ores as well as secondary resources.

Next-generation sequencing can also play an important role to raise bioleaching application at industrial scale. This technique is accelerating progress in genomic studies of bioleaching microbes from acid mining conditions. By 2016, 157 genomic analyses of acidophilic bacteria was done through next-generation sequencing which quantified genomic expression level under different conditions and produced their genetic and metabolic models to propose ecophysiological interaction mechanism during bioleaching reaction (Zhou et al. 2018). Therefore, this technique can be a powerful tool to enhance bioleaching rate by deepen our understanding towards functional elements of the genome and revealing molecular mechanism involved in bioleaching process.

Mechanical processing is the prior requirement of hydrometallurgy and biohydrometallurgy techniques to recover metals. Currently, industries use high capacity range (200–500 kg/h) granulators to produce different particle size material and recover plastic, nonferrous and ferrous metallic components (Chauhan et al. 2018). Due to high efficiency rate, pyrometallurgy and hydrometallurgy are still suitable techniques opted at industrial scale for leaching different metallic components. However, there are environmental risks and concerns associated with these techniques.

Chelation, membrane filtration, photocatalysis, and green adsorption are some of the novel alternative techniques which

have been recently considered for metals extraction from contaminated sites. Chelation technology involves stable metal-ligand complex formation. DTPA (diethylene triamine pentaacetate), oxalate, tartrate, and EDTA are some of the ecofriendly chelating agents used for extraction of some hazardous metals from contaminated soil. Reusability and ecofriendly behavior of chelating agents are key factors which provide attention to this technology in the field of medicine and environmental remediation. Photocatalysis is a recently developed process which utilizes photons from UV range and degrades pollutants. However, utilization of this process for metal recovery is still at infancy stage. Green adsorption is another green and economical technology which utilizes agriculture residues as metal adsorbents. Membrane filtration is costly and energy demanding as it requires membrane regeneration (Chauhan et al. 2018). None of these alternatives have been implemented for metals extraction from e-waste. Thus future attempt should be prompted to explore applicability of these novel technologies for metal extraction from e-waste. Computational tools may also be helpful to identify capable biodegradable chelating agents and adsorbents for metals recovery from WEEE.

Conclusions

Rapid improvements and technological innovation in EEE have increased the WEEE generation globally. Hence, e-waste recycling not only provides the opportunity for point treatment but also helps us in conserving our natural resources by recovering the precious metals. Current review encourages the need for extensive research to develop innovative, economical and ecofriendly approaches to extract metals from WEEE. Taking into account the 3Rs (reduce, reuse, and recycle) policy, high importance is given on reusing and recycling the electronic waste to decrease e-waste quantity ending up at dumping area. So far, various approaches like hydrometallurgical, pyrometallurgical, and biohydrometallurgical are being utilized for metals recovery from WEEE, but not a single technique can serve as a complete approach because of certain limitations associated with it, so there is need for the exploration of clean technology to recover metal from WEEE. It is evident that biohydrometallurgy probably to be hotspot in the near future. Effort to explore new relevant strains and their interaction with mineral surfaces in mixed species culture, as well as development of biomarkers to study associated microbial biodiversity may enhance knowledge for future bioleaching process. Further, use of some hybrid methods and sophisticated process design can enhance bioleaching efficiencies for industrial scale application.

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