

Towards sustainable metal recovery from e-waste: A mini review

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ABSTRACT

E-waste seems to be the major concern in present day technological world. It is the high time to treat the e-waste and to prevent various adverse effects from e-waste pollution. Heavy metals present in the e-waste raises the concern to be worried. Various research and studies have been focused and developed on e-waste recycling. Apart from this, heavy metal and valuable metal recovery from various e-waste seems to be economical. For the metal leaching process various leaching methods are involved. In this review, effects of e-waste, its composition and various methods available for treating e-waste and heavy metal leaching like chemical leaching and bio-leaching and factors affecting the leaching mechanism have been reviewed.

1. Introduction

E-waste production is increasing rapidly with the current trends of industrialization. These e-wastes are generally associated with very short life span of electronic equipment and rapid development of information technology [1]. Once the electronic equipment attains its end lifecycle it becomes e-waste. Generally, E-waste is categorized into six groups as large equipment, small equipment, small information exchange equipment, Screens and monitors, temperature exchange equipment and lamps [2]. E-waste generation started to increase at higher rate when various electrical and electronic devices become more affordable and people tend to buy new equipment rather than opting to repair. Countries with higher production of e-wastes are China, USA followed by India, Japan and Brazil [3]. It is one of the complex wastes produced by the society. The major problem associated with the recycling and treatment of e-waste is generally because of its heterogeneous material and complex composition. Heterogeneity is always associated with application of the equipment [4]. The chemical compositions of e-waste mostly vary depending on the type and age of the discarded item and their combination with other plastics and ceramics which are generally used as coating materials for these electronic items. Most common heavy metals found during the e-waste treatment process are both hazardous (Mercury, lead, Cadmium, Nickel etc.) and valuable materials (Copper, Platinum and gold) [5].

E-waste affects not only the environment but has various adverse effects on human health due to improper disposal, as e-wastes contain various heavy and toxic metals. These toxic elements either can be released directly or generated during the recycling process. E-wastes if

treated and recycled properly they have high commercial value because of its components. So, the research and studies should focus not only on recycling and treatment of e-wastes but should also focus on gaining commercial value by adopting various measures like reusing and resource recovery process [6]. Recycling of e-wastes can recover some valuable materials like Cu and Au. Most countries don't tend to recycle e-wastes due to lack of facilities, no proper methods of treatment and strict environmental regulations. Some countries even export e-waste to other poor countries where these wastes are either landfilled or recycled by stone age techniques [7]. They will eventually end up untreated in soil or in water affecting the ecosystems causing harmful effects on environment and Human health.

Heavy metals seem to be the major risk associated with the e-waste pollution. As these heavy metals have the ability to contaminate the soil microflora and Human health through accumulation in plants and animals at the e-waste dumping site [8]. E-waste sites develop a consortium of both organic pollutants and heavy metals which will undergo various chemical and metabolic changes from preventing the binding of enzymes responsible for degrading the organic pollutants [9]. This consortium is the major problem associated with e-waste recycling methods. Heavy metals released from e-waste or generated during the recycling of e-waste affect the soil ecosystem by bringing changes in the soil microbes. Heavy metals possess some serious implications on soil microbes by inhibiting various metabolic functions like protein synthesis [10]. Various studies have been focused and developed to assess the effect of these heavy metals on the soil ecosystem. Heavy metal exposure can also lead to development of metal-tolerant microbial populations [11]. This review article covers the composition

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Table 1
Metal compositions of various e-wastes.

E-waste	Metal concentration (ppm)	Reference
Dish washers	Al - (1.3–2.0)	[14,15]
	Sn - (1.6–2.0)	
	Cu - (2.0–4.1)	
	Ag - (0.0042–0.045)	
	Pb - (0.021–2.5)	
Vacuum cleaners	Cd - (0.036–1.9)	[16]
	Cu - (18.8)	
	Pb - (4.79)	
	Al - (0.912)	
Telephone	Cr, Cd, Ni - (0.0051–0.0179)	[4,15]
	Cu - (7.0–30)	
	Al - (1.41–14.17)	
	Pb - (1.20–6.29)	
Refrigerators	Sn - (1.0–3.15)	[14,15]
	Ni - (0.85–2.5)	
	Al - (1.3–2.0)	
	Sn - (1.6–2.0)	
	Cu - (2.0–4.1)	
Television	Ag - (0.0042–0.045)	[17]
	Pb - (0.021–2.5)	
	Cd - (0.036–1.9)	
	Cu - (10)	
	Al - (10)	
	Pb - (1.0)	
	Ni - (0.3)	

and characteristics of various e-waste material and methods adapted for resource recovery and effects of e-waste on environment.

2. An overview of the composition of e-waste

E-waste is composed of segments that are derived from a variety of materials around the globe, and such segments showing various units. It is a complex and diverse mixture. The diversity of e-waste increases the complexity of recycling e-waste. In order to explore and find the refining techniques that match the physical and chemical properties of different elements in the composition e-waste are characterized. Hence, elements are an integral part of multiple e-waste types. It contains both toxic materials and various precious metals [12]. The other stuffs are plastics, pollutants, mixture of plastic-metals.

2.1. Hazardous metals from e-waste

There are strict e-waste policies in developed countries and higher costs associated with recycling hazardous substances which motivates the refining technologies. Heavy metals such as lead, mercury, chromium, and cadmium are common components of e-waste [13]. The metal composition of various eWaste is listed in Table 1. They are reported to be hazardous in nature. The recovery of toxic elements such as Cr, Hg, Ni and Pb are from the electronic waste has been shown in a work of Kuntawee et al., 2020 [18] and they are widely used in electronic goods for various purposes [19]. An initial study found elevated levels of toxic heavy metals, including chromium, lead, cadmium, and organic contaminants in samples of dust, soil, river sediment, surface water, and ground water sources in Guiyu, China [20]. Metals such as lead are most commonly used in electronic devices for different purposes, causing numerous health hazards due to environmental contamination [21], it is a silvery-white metal that is highly ductile and rarely found in its native state in nature, but when combined with other elements, it can form a variety of interesting and beautiful minerals. One of its physical properties is that it exists in its solid form under normal environmental conditions [22]. The ubiquity of cadmium (Cd) in the environment and bioaccumulation of Cd in organisms have caused a variety of adverse effects in mammals [23]. However, the electronic waste material can be developed into a novel adsorbent to

treat heavy metal loaded waste derived from waste PCBs [24].

One of the toxic heavy metals is chromium (Cr). It is usually used in electronic devices for a variety of purposes, including cosmetic purposes. Chromium typically exists in two stable states such as trivalent chromium [Cr(III)] and hexavalent chromium [Cr(VI)]. The trace element Cr(III) plays a critical role in glucose and cholesterol metabolism, but excessive intake of it may have negative effects. The compound Cr(VI) is 1000 times more toxic than Cr(III) [20]. As for mercury, it can be found in LCD backlights, lamp components, display panels, and so on. Although the amounts contained in each EEE unit are not high, mercury is still present. Various industries have used mercury as a catalyst for chemical reactions or for producing chemicals for many years due to its unique properties. It occurs naturally in the environment [25]. Toxic substances which have been banned, cancelled or refused registration by the government for reasons relevant to human health or the environment, or have voluntarily been withdrawn from registration in the country of manufacture [26].

2.2. Precious metals from e-waste

Metals such as gold, silver, platinum, copper, aluminium, nickel, tin, zinc, lead, and iron are considered to be valuable metals present in electronic waste, as are base metals, such as nickel, cobalt, zinc, lead, and others (Hg, Be, In, Pb, Cd, As, Sb) [13]. Even though precious metals (listed in Table 2) are much lower than base metals in Waste-Printed Circuit Boards (WPCBs), they are much higher than those in any conventional ore. Traditionally, precious metals are recovered from ores by smelting and refining them [30]. In the production of mobile phones and personal computers, 3% of the gold and silver mined worldwide is utilized; 13% is utilized for palladium and 15% is utilized for cobalt. Using hydrometallurgical techniques to recover precious metals and has been one of the most active research areas since the 1980s [31]. As a refining process of precious metals, aqua regia was introduced as a leaching factor in the second stage, and this resulted in low percentages of copper and silver, but gold was recovered at 18%. Utilization of hot aqua regia could improve silver and gold recovery [32].

3. Environmental and health impacts of e-waste

The potential adverse health effects of toxic substances in e-waste are influenced by their concentration, on-site location, and duration of exposure [18]. As the population grows, electronic gadgets are becoming more and more prevalent in day-to-day life. If electronic goods usage increases, e-waste generation will increase as well. In the absence of proper disposal or recovery of e-waste, they will cause serious environmental pollution, if not even harm to human health [12]. Many

Table 2
Precious metal compositions of various e-wastes.

E-waste	Precious metal concentration (per kg of e-waste)	Reference
TV Board	Ag - (280 g)	[27]
	Au - (20 g)	
	Pd - (10 g)	
Computer	Ag - (200 g)	[28]
	Au - (2 kg)	
	Pd - (100 g)	
Television	Ag - (100 g)	[17]
	Au - (700 g)	
	Pd - (40 g)	
Circuit boards	Au - (200 g)	[29]
	Ag - (6 kg)	
	Pd - (0.50 g)	
Calculator	Au - (6 g)	[4]
	Ag - (76 g)	
	Pd - (3 g)	

heavy metals will remain in the soil for thousands of years, posing numerous health risks to higher life forms. A heavy metal is one that interferes with plant growth, affects ground cover, and negatively impacts soil microflora. It is well known that heavy metals cannot be chemically degraded, but must be physically removed or transformed into nontoxic compounds to stay away from the global environment [22]. During the management and processing of e-waste because of the hazardous substances contained within, such as heavy metals and other chemicals, it can pose a threat to the environment and human health [19]. A study revealed that lead (Pb) can affect the liver, kidneys, and nervous system and disrupt cognitive development. In addition to respiratory and kidney damage, and weakened immune systems, chromium (VI) can cause cancer of the nasal, sinuses, or lungs. Asthma and dermatitis may be caused by nickel (Ni). As well as that, Mercury (Hg) exposure may cause memory loss, immune dysfunction, and muscle weakness [18]. In animal health, during embryonic development, each of the Cr(III) and Cr(VI) compounds causes neuronal tube defects, malformations, and even death in mice. Additionally, the Cr(VI) compounds are known environmental contaminants and occupational carcinogens for humans [20].

4. General metal recovery of e-waste

A toxic and non-toxic metal can be extracted through various methods and techniques. Elements can be derived through chemical, mechanical, and biological processes, and metallurgy is the study of the behaviour of metals under various properties. There are two main approaches to metal restoration: hydrometallurgy, where metals are leached by the process catalysis, and pyrometallurgy, which is all about the thermoconditioning process using methods such as acid leaching and caustic leaching, salt roasting, smelting and calcination, chlorination, chelation, etc. Table 3 lists the advantages and disadvantages of various leaching mechanisms. Then Bio-hydrometallurgy, which is cheaper and more eco-friendly than either of the other two methods. It is simple and does not require complex machinery. It is also possible to perform the bioleaching at mild conditions, hence it is called a clean technology [35].

4.1. Hydrometallurgy

A hydrometallurgical process is a metal extraction process using chemicals that separates the metallic elements based on the aqua medium reactors [36]. It has been developed in 1887 by the invention of two special methods, the cyanidation method and the Bayer method, which were treated for the extraction of alumina and gold ores. As the 20th century progressed, they discovered the leaching process as the most excellent method of recovering metals [37]. In this type of two step method, precious metals are extracted through dissolution in a specific leaching agent, and then the metal can be recovered through different precipitation [38]. It is common for a metal to be leached from at relatively low temperatures, usually under 200 °C [39]. As a direct or indirect leaching method, metallic elements are leached by an appropriate alkaline or acidic reagent in the existence of oxygen, chlorine, iodine, bromine, hydrogen peroxide, etc [40]. According to historical records, during the first world war there was a great need for zinc to manufacture brass, which was obtained from random metals obtained from Germany and Belgium by utilizing this chemical leaching method [41]. In fact, platinum metal can even be leached through the use of this method under definite oxidizing conditions by using certain ion exchange and different lixivants, such as hydrochloric acid, sulphuric acid, nitric acid, and iodine solutions [40]. It can be accomplished using several different chemicals, and the chemical composition will directly affect the process' economics and environmental sustainability [38]. In chemical leaching, four types of leaching have been distinguished: Cyanide leaching, Halide leaching, Thiosulfate leaching, Thiourea leaching, and Aqua regia leaching.

Table 3
Advantages and disadvantages of various leaching mechanisms.

Methods	Sub-Process	Advantage	Disadvantage	References
Hydrometallurgy	Cyanide leaching	Low energy consumption, no need for oxidant or catalyst	Health hazards while leaching process	[33]
	Halide leaching	High recovery rate, lesser energy consumption	Vigorous corrosive and oxidizing circumstances	
	Thiosulfate leaching	High recovery rate, lesser energy consumption	Slower process and thiosulphate utilisation will be higher	
Pyrometallurgy	Thiourea leaching	Less toxicity and reduced energy consumption	High consumption and not economically feasible	[33]
	Alkali smelting	Formation of toxic compounds (furans and dioxins) can be avoided	Molten alkali compound	
	Plasma melting technology	High recovery rate, lower waste production	Consumption of more energy	

4.1.1. Cyanide leaching

Metals are extracted from the ore through a leaching process where the elements are leached out with a solvent called leaching reagent. It's almost the process of letting solids into the water phase. Cyanide is a chemical reagent used as a lixiviant that is considered one of the best and cheaper reagents to confine gold when mixed through a suspicious alkaline solution. In extraction of gold or silver at the surface of Polychlorinated biphenyls (PCBs), cyanide leaching is one of the top most effective method [42]. Among the processes for recovering precious metals like gold from ores, the cyanidation process is considered to be one of the most important ones. There is a historical fact that aerated cyanide reagents will aid in the process to produce gold cyanide metal [43]. There is huge amount of wastewater containing cyanide, known to be toxic to humans, which still control the gold mining industry and its leaching process. Cyanide can be dangerous for gold miners as well. As this cyanidation process leaches slowly, the production process will be lengthy [42].

4.1.2. Halide leaching

Halide leaching is a variation of three kinds of chemical reagents: bromide leaching, iodide leaching, and chlorite leaching. And its rate of leaching is quite high. With different solution chemical conditions, gold forms both Au^+ and Au^{3+} complexes with chloride, bromide, and iodide. Chlorine and chloride are the only halides used industrially on a notable scale where this chloride leaching and corrosion has a wide link, just to prevent deterioration the equipment's are manufactured with rubber and stainless steel [42].

4.1.3. Thiosulfate and poly-sulfate leaching

Thiosulfate leaching is one of the hydrometallurgy methods used in leaching gold (Au). In presence of oxygen, the gold metal and the reagent thiosulfate will get well together to form a fixed complex. Sodium thiosulfate and ammonium thiosulfate are two kinds of thiosulfates used for precious metals leaching [42]. Due to the simultaneous presence of complexing ligands like ammonia and thiosulphate, the chemistry of the ammonia-thiosulphate system is quite complicated. It is possible to form tetrathionate through the oxidative breakdown of thiosulfate via the redox equation [44]. Under alkaline conditions of an ore, gold metals are stable in medium of alkaline because tetrathionate, the oxidation product of thiosulfate, will be converted back into thiosulfate [42]. In thiosulphate leaching, excessive consumption of thiosulphate is a major problem. This occurs mainly due to thiosulphate decomposition in solutions containing copper [45].

In poly-sulfate leaching, certain metal sulfides like zinc sulfide, Chalcopyrite, Arsenopyrite, Lead(II) sulfide, and Manganese(II) sulfide, can be broken up by the federated effects of ferric ion particles. In the presence of the proton, metal and sulfur molecules form a hydrogen disulfide radical, which is changed into hydrogen disulfide by the strike of such proton. Additionally, it is converted into natural sulfur via higher polysulfides and polysulfide radicals. It is therefore referred to as the polysulfide mechanism of chemical leaching [46].

4.1.4. Thiourea leaching

An organic reducing agent with stable complex was first synthesized in 1868. It is said to form a strong bond not only with precious metals, but also with some base metals like copper [47]. In a study, it was found that this reagent of sulfurized urea (Thiourea) could form complexes of white crystal with many ions. Under certain acidic conditions, gold and thiourea will form soluble cationic complexes, especially when an oxidant is present such chemical reactions take place to leach a metal from ore [42]. Potentially, this can be applied to develop cheap bio-leaching technologies for precious metals targeting both e-wastes and natural gold bearing ores [47].

4.2. Pyrometallurgy

Pyrometallurgy is a conventional heating process of metal recovery and precious metals from waste electrical and electronic equipment under industrial used technology [48,49]. Pyrometallurgical processes produce a lot of solid residues, such as slag, sludge, ash, and other products by, incineration, smelting, conflagrating, drossing, sintering, and melting at high temperatures. Furthermore, slags may contain toxic elements, making their handling to be done under safety manners [48,50]. Metallic oxides react with reducing agents like charcoal or coke to liberate carbon dioxide (CO_2) in specialized incinerators, blast furnaces, and plasma arc furnaces [51]. Smelting takes place in furnaces, where the scrap is generally smelted either via flash or bath smelting. Air and oxygen are the main inputs for the process, as well as aluminium oxide, calcium oxide, silicon dioxide, and calcium oxide [49]. In serious note, comparing to other two metal recovery techniques pyrometallurgy cause major air pollution, it's even recorded in a study that the smelting of electronic waste emits a large number of harmful compounds, gases such as polybrominated dibenzofurans, naphthalene, biphenyl, dibromobenzene, dibenzodioxin, tribromobenzene, polybrominated dibenzodioxins, dibenzodioxin, etc. There is also evidence to suggest that the processing of electronic waste in open burning sites emits large quantities of toxic heavy metals such as mercury, zinc, and polychlorinated dibenzodioxins and dibenzofurans that lead to non-exceptional ecological and health issues. In this process, the final product has a low yield and produces higher losses of metals which are lost in slag, on refractories, or as dust [51].

4.3. Biohydrometallurgy

This is a field in which biology and hydrometallurgy intersect in a variety of biological relationships between metals and minerals and use of microbes for metal recovery. In simple words, microorganisms are applied to the processing of metals in aqueous media for the study of metal extraction [52]. Sulfide minerals are stripped of their metals by a process of bioleaching in which microorganisms play a significant role in the process [53]. Biohydrometallurgy is generally known as bioleaching, which is the most emerging technology for metal extraction from e-waste. It can be performed by direct or indirect method and mostly used in terms of extracting precious metals [54]. It is usually understood that direct bioleaching refers to a process by which solid metals are converted to water-soluble forms through the action of microorganisms. Copper, for example, is oxidized by microorganisms to copper sulfate and metal values appear in the aqueous phase, while the solid remains are discarded [55]. Indirect bioleaching of sulfide minerals is facilitated by the supply of oxidizing oxidants from microorganisms. The amount of elemental sulfuric acid produced by indirect bioleaching can be controlled [52]. In some cases, this process of bioleaching is also called as bio-oxidation in which metal sulphides that contain no value are oxidised and removed from ores bearing value in the form of dissolving mechanism. In the case of arsenopyrite bioleaching, for example, sulfides of iron and arsenic are solubilised and the remaining precious metal gold is recovered by cyanidation [56]. The first step in the metal recovery method is oxidation. Usually, Fe ions are used for the oxidation of the ore. This step is totally independent from microbes. The next step includes the role of bacteria for the regeneration of chemical reaction by oxidizing Fe^{2+} to Fe^{3+} . In reality, bacteria catalyse the breakdown of the Fe^{2+} by oxidizing the sulfur and metal, so they use oxygen to break down the iron. During microbial oxidation, the cell membrane of the bacteria is exposed to oxygen. By transferring electrons into the bacteria, the bacteria are able to produce energy while reducing oxygen to water via biochemical processes. As mentioned above, the bacterial step is responsible for producing this reactant [57]. The ability of microorganisms involved in these transformations, primarily bacteria of the subfamily: *Thiobacillus* and *Leptospirillum*, to adapt in highly acidic nature with heavy metal

takes this technique to the next level process. The only drawback is that they need long period of time for the solubilization of uranium. The uranium ore is leached with ferric sulphate, which is produced by bacteria from pyrite in the ore and can, in turn, be regenerated by the bacteria [58]. During bacterial leaching, metal ions stay in solution at pH values between 1.5 and 3 due to the acidic environment [59].

Historically, Copper leaching and precipitating mechanism from ore solutions have been practiced by the Chinese since at least 100–200 BC and even earlier. Although microorganisms were evidently not used before the 1940 s in metal solubilization processes. For several decades, Rio Tinto Mines conducted industrial leaching operations, but the first discovered microbial leaching was done with the bacteria *Thiobacillus ferrooxidans* [55]. In 1980, copper heap leaching was the first application of biohydrometallurgy, geared toward facilitating microorganism activity. Another report describes biooxidation pre-treatment of refractory sulfidic gold ores to expose gold concealed within sulfide minerals using microorganisms to oxidize pyrites, arsenopyrites, or arsenianpyrites [60]. BRISA, heap bioleaching, and stirred tank biooxidation of mixed concentrates are discussed as recent developments in biohydrometallurgy of zinc [61]. The sludge digestion process for bioleaching is more efficient. Therefore, bioleaching of sewage sludge may be regarded as a suitable technology for producing Class A biosolids that are suitable for agricultural use [62]. In comparison with chemical leaching, optimizing bioleaching conditions is more challenging due to the possibility of metal toxicity on microorganisms and the resulting concerns over microbial activity [50].

4.3.1. Recycling mechanisms of bioleaching

The microbial leaching can be done through two mechanisms – direct and indirect method. Direct bioleaching which occurs in the presence of microorganism and includes two basic methods classified as one-step bioleaching and two-step bioleaching. The one-step bioleaching involves the inclusion of the microorganism and the used catalyst in the same medium. Where the two-step bioleaching technique consists of adding the microorganism first, and then adding the spent catalyst once biometabolite production starts. In indirect bioleaching, biometabolites are produced by microorganisms after a period of time without them [35]. In a study, bioleaching was performed by the microbe acidophiles under both of the direct and indirect leaching mechanisms. In these mechanisms, acidophiles oxidize ferrous (Fe^{2+}) and reduced sulfur species respectively into ferric (Fe^{3+}) and sulphuric acid [56]. The indirect process is thought to be the best method for increasing leaching efficiency in industrial applications. The positivity of an indirect bioleaching process is that the liquid medium generation is independent of the chemical reaction, so there is no link between the two reactions and that makes it to perform alone to grow its productivity [35].

4.3.1.1. Direct bioleaching. This mechanism involves the attachment of bacteria '*Acidithiobacillus ferrooxidans*' to the surface of an ore with the assistance of polymeric substances. After certain time, ore will become infested with bacteria to a corner. Fe^{3+} bound to glucuronic acid in the EPS layer of the bacteria is reduced to Fe^{2+} + by taking one electron from ore. Later, by reoxidizing the resultant Fe^{2+} to Fe^{3+} , cytochrome re-enacts this reaction. The removed electron is transferred to oxygen by periplasmic cytochrome and cytochrome oxidase. In this way, oxygen is reduced to water, which results in the synthesis of ATP by microbes. Ore extracts electrons from glucouroinic acids in EPS by attracting Fe^{3+} from solution. The element undergoes this reaction and decomposes into thiosulphate and metal cation. Biochemically, elemental sulphur can form aggregates in the periplasmic space and oxidize to sulphuric acid [56]. It is based on the idea that a metal sulfide attached to a cell will oxidize the mineral with oxygen and form sulfate and metal ions. The sulfur in the mineral is believed to be biologically oxidized, without any intermediates being formed [63]. Yang et al., 2008 [64] performed a comparison of one-step and two-step

bioleaching of heavy metal recovery by experimenting by using *Aspergillus niger* as a microbe. In simple words he described the one-step bioleaching method, in which fly ash is added to the culture medium at the start of the bioleaching. The two-step bioleaching method, in which fly ash is added to the culture medium after preculturing for a few days [64]. It is preferable to go with the two-step process due to its easy handling, which allows optimization and control of steps [65]. To increase the leaching efficiency of microorganisms from e-waste, two step method of bioleaching are likely to be appropriate [66].

4.3.1.2. Indirect bioleaching. Indirect mechanisms work by dissolving metal sulfides using iron III ions. It is expected that iron II ions and the element sulfur will be generated as a result of this chemical reaction. Again, biological oxidation converts them into iron III ions and sulfates [63]. In the solution, regenerated Fe^{3+} combined with sulphuric acid are ready to dissolve the metal from the ore/mineral. These steps do not require the participation of microbes. Thus, microorganisms are added after contact time is the indirect method [56].

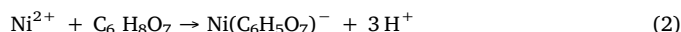
4.3.2. Mechanisms involved in bioleaching

A number of mechanisms involving acidolysis, redoxolysis, and complexolysis were present in the e-waste using the microbial metabolites [65].

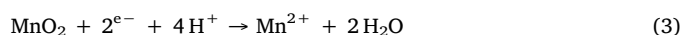
4.3.2.1. Acidolysis. The leaching process is primarily a reaction between an oxide and protons [64]. In acidolysis, protons are used to oxidize organic acids produced by fungi. This reaction weakens critical bonds on the ore surface, thus removing metal ions is mentioned in the below equation [35].



4.3.2.2. Complexolysis. During complexolysis, metal ions are stabilised by chelation through acidolysis. Metal(s) and organic acid(s) combine to stabilise molecules. As well as amino acids produced by fungi, organic acids which are released by them are also capable of complexolysing and providing protons for metal solubilization. However, filamentous fungi rarely secrete amino acids, so amino acids do not contribute much to this process. An equation stated below, representing a standard complexolysis reaction that results in Ni solubilisation as Ni-citrate [35].



4.3.2.3. Redoxolysis. Redoxolysis, on the other hand, is the microbial process of oxidating or reducing metals. The increase in metal mobility depends on the oxidation state and type of metal. When manganese is leached by fungus, it is soluble due to enzymatic reduction of highly oxidised manganese, as shown in equation [35].



4.3.3. Bioleaching using microorganisms

Microorganisms plays a vital role in biological leaching of metals. Most of the utilised microbes are acidophilic bacteria, acinetobacteria, archaea and fungi. Where the fungi take down three major reactions – acidolysis, complexolysis, redolysis. Microbial communities of acidophiles can be divided into three classes: mesophiles, moderate thermophiles, and extreme thermophiles as per the growth temperature [56]. *Acidithiobacillus* and *Leptospirillum* are mesophilic bacteria grown at 30 °C. *Sulfobacillus*, a moderate thermophile that thrives at temperatures of 40–60 °C. In the temperature range of 60–90 °C, extreme thermophiles include *Sulfurococcus*, *Sulfolobus*, *Metallosphaera*, and *Acidanus* [46]. When the temperature of the bioleaching consortia is

70 °C, the only organism to bear extreme heat is archaea such as *Sulfolobus* and *Metallosphaera* dominate. The stages of microorganisms are defined as chemolithotrophs and autotrophs. In bioleaching, microorganisms that dissolve sulfide minerals are typically chemolithotrophs, which metabolize atmospheric CO₂ and grow autotrophically. While most autotrophic organisms obtain energy from sunlight, chemolithotrophs obtain their energy from either ferrous iron or reduced inorganic sulfur compounds [61].

4.3.3.1. Bacteria. Bacteria are free living organisms that exist all around the environment, its role in biohydrometallurgy is demandable. Mesophilic and thermophilic are the two important and active microbes of bioleaching. Lately, these two extremes of bacteria are playing a vibrant role industrial bioleaching technique. The mines and metallurgical industries make extensive use of mesophilic bacteria such as *Acidithiobacillus ferrooxidans*, *Acidithiobacillus thiooxidans*, and *Leptospirillum ferrooxidans* as iron and sulphur-oxidizing bacteria [53]. These are chemolithoautotrophic mesophilic bacteria, which rely on inorganic elements for energy reproduction, such as sulfate and ferrous ions. It grows best at temperatures ranging from 28° to 37°C and synthesise cell material from Carbon dioxide. And the bacteria *Acidithiobacillus ferrooxidans* generates energy by oxidising Fe²⁺ [56]. *Thiobacillus*, the most efficient bacterial family in bioleaching is a gram-negative rod-shaped microbe which grows in aerobic conditions. They are mostly chemolithoautotrophic, indicating that they use carbon dioxide from the atmosphere to produce new cell material [59]. Individual cultures of acidophilic chemolithotrophic bacteria and acidophilic heterotrophic bacteria were shown to have less bioleaching capability than mixed cultures. Moderate thermophiles have been shown to have increased rates of bioleaching metals from ores than mesophiles, and in certain cases even greater than intense thermophiles. Ilyas et al., 2010 [67] used both the *Sulfobacillus thermosulfidooxidans* and *Thermoplasma acidophilum* for bioleaching operation. Serial sub-culturing was used to adapt moderately thermophilic cultures to various metal ions such as Ag⁺, Ni²⁺, Pb²⁺, Sn²⁺, Al³⁺, Cu²⁺, Fe³⁺, and Zn²⁺. It confirmed the presence of two metals, including Sn and Pb. The prolonged study also stated the number of metals recovered from the source as aluminium 0.65 ± 0.08, copper 1.88 ± 0.05, iron 2.5 ± 0.07, lead 27.0 ± 0.08, nickel 0.22 ± 0.005, tin 74 ± 0.07 and zinc 0.10 ± 0.01% [67].

Here, various studies of bacterial strains used in bioleaching and the recovered metal percentages were discussed. Karwowska et al., 2014 [68] cultivated surfactant-producing *Bacillus subtilis* PCM 2021 and *Bacillus cereus* PCM 2019 strains in a medium with 6 g/L Na₂HPO₄, 3 g/L KH₂PO₄, 0.5 g/L NaCl, 0.25 mg/L yeast extract, starch and peptone, and 2 mL plant oil. In the bioleaching medium containing both sulphur-oxidising and biosurfactant-producing bacteria, active sulphuric acid extraction by *A. thiooxidans* bacteria was discovered. Further, the M-I medium containing both sulphur-oxidising and biosurfactant-producing bacteria, aeration of the bioleaching medium enhanced the release of Ni, Cu, Zn, and Cr but not Cd and Pb [68]. *Sulfobacillus thermosulfidooxidans* consortia with *Thermoplasma acidophilum* and *Sulfobacillus acidophilus* consortia with *Sulfobacillus acidophilus* were cultivated at 45 °C in another investigation in 2013 [69]. From processed electronic scrap, a consortium of *Sulfobacillus thermosulfidooxidans* and *Thermoplasma acidophilum* recovered roughly 85% Cu, 75% Al, 80% Ni, and 80% Zn. A consortium of such bacteria that included FeS²⁺S⁰ recovered 90% of Cu, 80% of Al, 82% of Ni, and 85% of Zn. Approximately 74% Zn, 68% Al, 85% Cu, and 78% Ni were leached away during 165-day column bioleaching tests were reported [69]. *Thiobacillus ferrooxidans* is a highly acidic bacterium whose 23 strains were cultured and differentiated for a study by Vera et al., 2013 [70] by DNA-DNA hybridization pattern. Later, the *Acidithiobacillus ferrivorans* strains were alone removed from the sub group and taken to extract metals from sulfur mine dumps which is represented as a novel specie. Because of their psychrophilic growth condition and motility, these species may be the most common bacteria in low-temperature

leaching situations [70].

A two-step bioleaching technique was used to explore the bioleaching of Cu and Au with the help of cyanogenic bacteria. The *Chromobacterium violaceum* was isolated by optimising temperature, pH, and glycine proportions to attain maximum Cu and Au bioleaching. *C. violaceum* bioleached Cu and Au from WPCBs (waste printed circuit boards) and recovered 87.58% and 73.63% of the metals, respectively [71]. It has been stated in an experiment that Cu 79.3%, Au 69.3%, Zn 46.12%, Fe 9.86%, and Ag 7.08%, accordingly, were bioleached the most by the similar bacterial strain *C. violaceum*, which was followed by *Pseudomonas aeruginosa*. The mixture of *P. aeruginosa* and *C. violaceum* had the highest bioleachability among mixed cultures, with 83% of Cu, 73% of Au, 49% of Zn, 13% of Fe and 8% Ag. In the combination of two cultures, the highly recovered metal percentage of gold can be seen. This could be owing to a better tolerance for toxic effect, the establishment of persistent breakdown of metals in the presence of electronic waste that releases metabolites for bioleaching, or a combination of these factors [66]. Since *Chromobacterium violaceum*, *Pseudomonas fluorescens* are capable of producing hydrocyanic acid (HCN) which can dissolve gold, these cyanogenic bacteria are considered as the top most essential of bioleaching. This study used a bacterial strain isolated from ferruginous mineral waters. The copper extraction process is accelerated by a higher dose of bacteria cultures, which results in a higher concentration of Fe³⁺ ions in solution, which oxidise basic copper to copper ion as per the reaction. Copper samples injected with 50% and 100% bacteria were leached in 60% [72]. Another study with these bacterial colonies shows the individual identity of the isolated SAE 1. Under optimal conditions, *Pseudomonas balearica* SAE1 was able to leach 68.5% and 33.8% Au and Ag, respectively [73].

4.3.3.2. Fungi. Fungi has a huge participation in bioleaching methods, because it has the ability to produce organic acids as the major carbon source [56,74]. The supplements of organic acids are citric acid, gluconic acid and oxalic acid. The secretion of fungi organelle organic acids produces three chemical reactions for solubilisation of carbons are acidolysis, complexolysis and redoxolysis [56]. Metal leaching by fungi has been documented in several papers. Fungi from the *Aspergillus* and *Penicillium* genera have been found to be among the most productive and significant for biological leaching. *Aspergillus foetidus* was bred to be a multi-metal resistant fungus after being exposed to a wide range of metals such as Zn, Ni, Al, Co, Cr, Cu, Fe, Mn and Mg. As a result, rather from being considered waste, these by-products are regarded secondary sources of metals, and fungal bioleaching is a feasible recycling process [74]. According to a study, pure and mixed fungal cultures of *Aspergillus tubingensis*, a polymer composting species, and *Aspergillus niger*, an organic acid producing species, can bioleach metals from waste PCB at a pulp density of 1 g/L in 33 days. This demonstrates the perusal and approval of employing pure and mixed cultures of *Aspergillus tubingensis* and *Aspergillus niger* to bioleach metals from e-waste. When pure and mixed forms of *Aspergillus* fungal strains were used to extract metals from e-waste, it was discovered that *Aspergillus niger* was able to leach off more metals than *Aspergillus tubingensis*. This study found that 63% of aspergillus strains were effective at extracting Zn metal [75]. Bioleaching of metals from batteries by *Aspergillus* species, including *Aspergillus niger* and *Aspergillus tubingensis*. This method is cost-effective, environmentally beneficial, and innovative way to recover valuable metals from many types of e-waste [76] and the frequent optimised pH and temperature of fungal bioleaching are 3–7 and 25–35 °C [56]. Faraji et al., 2018 [77] stated in an experiment that *Aspergillus niger* is one of the gradient valuable metal recoveries from WPCBs. At first, he written about the optimising of leaching parameters for fungi chemical mechanisms. Then about the kinetic mechanism between the metals and microbes [77].

4.3.3.3. Acinetobacteria. It is gram-negative bacteria which has the ability to achieve 23% of copper recovery under the acidic condition of batch mode operator. The metabolites, biomass and enzymes

produced from the acinetobacteria hands in to the bioleaching process. Lower bioleaching results of copper from e-waste could be due to inactivation of enzymes in the medium by leached copper ions, slowing metabolic processes and metabolite production, resulting in bioleaching, or cell apoptosis in the media due to nutritional deficiency, resulting in limited aerobic metabolism [78]. A study creates an environmentally benign method for recovering manganese (Mn) from waste remnants utilising *Acinetobacter* sp. Bioleaching test was conducted in shake flasks at 30 °C with stirring speed 200 rpm and *Acinetobacter* sp. as inoculum, with an initial pH of 6.5, 5% w/v inoculums, and 2% pulp density. In just 20 days, Mn was recovered at a rate of 76% [79].

5. Factors affecting techniques of bioleaching

Hence, understanding the mechanism by which these factors influence bioleaching is crucial in order to hasten the bioleaching rate, because maximal bioleaching can only be attained when these factors are well adjusted.

- Microbes

The most prominent species of bacteria aiding metal solubilization is chemolithoautotrophic acidophilic bacteria like *Leptospirillum ferrooxidans*, *A. ferrooxidans*, and *A. thiooxidans*, which obtain their energy from inorganic molecules such as Fe^{+2} and reduced sulphur, and carbon from CO_2 . Gold (Au) is obtained by cyanogenic bacteria like as *Cyanobacterium violaceum*, which live in an alkaline environment and produce cyanide, the main extracting component. Then, acidophilic bioleaching bacteria, biosurfactant-producing bacteria, and bacterial consortium from acid mine drainage in various combinations [51].

- Temperature

Temperature is an important factor that influences bacterial growth and, as a result, metal bioleaching. The ideal temperature for bioleaching is the one that favours metal dissolving the most, and can thus be linked to bacterial activity all across the metal process of extraction [51]. *Acidithiobacillus* thrives at temperatures between 28 and 35 degrees Celsius. Bioleaching investigations on electronic waste were taken out at 30 degrees Celsius. The efficacy of the technique at 22–25 °C was also investigated [72]. The distribution of microorganisms isolated on three media from tested substances at 30 °C resembles that of the bacteria recovered on three media from two samples at 20 °C, with a greater number of isolates at 30 °C. Thus, it is always important to optimize the temperature for phenomenal productivity [80].

- pH

The pH of the medium creates impact to the growth of bacteria, and controls metal solubilization. At an acidic pH of 2–2.5, the 95% of metals are recovered [51]. In the leaching of metals from solid phase to solution, besides the proportion of Fe^{3+} ions and the number of microbes, pH is considered as a major factor. In a specific study, the pH in the range of 1.5–2.0 adjusted by adding H_2SO_4 improved the efficiency of copper extraction using *A. ferrooxidans* in the bioleaching process [72]. The pH fluctuation in the leaching process of gold electronic scrap was monitored by two separate cyanogenic bacteria such as *C. violaceum* and *P. fluorescens*, who followed the same trend, and pH climbed steadily from 7.2 to roughly 9 for more efficient production [81].

- Nutrient

A suitable nutrition demand of the leaching medium is critical in bioleaching. Bacterial growth, metabolic activity, and metal solubilization are all influenced by the medium's contents [51].

- Aeration

In most cases, the bacteria participating in the bioleaching process are aerobic. For their growth and metabolism, they require appropriate

air supply. Hence, the appropriate aeration is much more important as the nutrient supply to the media [51].

6. Conclusion

E-waste is a largest growing sector with rising uses of electrical items worldwide. This is a consequence of versatility and affordability of technological innovation, thus resulting in massive sales and e-waste increases [82]. Currently, the metal recovery system is used in each and every square of the world. The enormous usage of metals such as pure metals and heavy metals shown its valuable participation in the economy. The continuous extraction of valuable metals from the ores are showcased and traded all over the world. The globe is revolving with vast number of peoples and their electronic gadgets. The wastage of these electronic appliances is listed as electronic waste i.e., e-waste. When these electronic wastes are thrown to garbage, they may release heavy toxic contents which expose to humans in kind of affecting their human health. To avoid such things, the waste can be decomposed by various techniques like recovering the toxic metal aside and this process is composting where the extraction of metal is known as leaching. The current bioleaching landscape is optimistic; nonetheless, research in this area is patchy, primarily performed on autotrophic microorganisms, and conducted on a laboratory sector with a wide range of different parameters. They even use heterotrophic leaching bacteria on easily available, low-cost organic wastes generated by the agro-food industry, for example, have a lot of potential stuffs to do [51]. Extracting metals from the electronic scraps is known to be the clean technology of the scientific evidence since it's been implemented for the process of cleaning the scraps of electronic devices [83].

To achieve sustainable recovery of precious minerals in sewage and industrial effluents, a common conceptual and perspective vision for non-rural mining of e-wastes is necessary. To enhance the recyclability of each metal, a novel idea of rare metal recovery complex is developed [84]. Local and global home appliances, computer technology and computer equipments, consumer devices, electrical & mechanical tools, medical instruments, and other e-waste items are among the most common scraps [56]. As a consequence, modern technologies must be built with their utility, reuse potential, and ultimate disposal in mind [85]. In absence of such fact for the most devices, they're disposed to the side of e-waste. This review article contributes the process of metal recovery [86], composition of e-waste, health deficiency caused by the hazardous metals, the process and studies of biological and chemical leaching of minerals.

Declaration of Interest

The authors declare that there is no conflict of Interest.

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