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Chapter

[4]

An overview on environmental pollution caused by heavy metals released from e-waste and their bioleaching

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Abstract

The consistently expanding quantum of e-waste is booming at an extremely high pace which is around 20-25 Mt for every year. The metal recovery from e-waste is a developing zone of scientific enthusiasm because of quality of wide scope of valuable metals present in it. Bioleaching can improve and recover the heterogenic metals present in electronic waste in a proficient way, thereby helps in its effective management. The microbial strains involved in metals bioleaching mobilize the metals under the influence of cyanide and acidic medium. *Acidithiobacillus thiooxidans*, *Thiobacillus ferrooxidans*, *Thermoplasma acidophilum*, *Chromobacterium violaceum*, *Acidithiobacillus* and *Aspergillus niger* are the major microbial strains engaged with metals bioleaching. This chapter emphasized on the types of microorganisms and their performance in metal bioleaching and inspects the bioleaching of gold, iron and copper from e-waste scrap. Additionally, the key environmental and health concerns associated with e-waste exposure are also discussed. Therefore, this chapter provides comprehensive information on eco-friendly and efficient bioleaching of heavy metals from environment.

Keywords Bioleaching, Electronic waste, Heavy metal recovery, Waste management

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Abbreviations: MoEFCC: Ministry of Environment, Forest and Climate change, EEE: Electrical and electronic equipment's, e-waste: Electronic waste, HF: Hydrofluoric acid, GEWM: Global e-waste monitor, Mt: metric tons, PCBs: Poly Chlorinated Biphenyls, BFR: Brominated flame retardants, PDA: Potato dextrose agar, SF_6: Sulphur hexafluoride, ICP-OES: Inductively coupled plasma-optical emission spectrometry, CRTs: Cathode ray tubes.

E-waste definition: According to e-waste (management) rules, 2016 *"e-waste' means electrical and electronic equipment, whole or in part discarded as waste by the consumer or bulk consumer as well as rejects from manufacturing, refurbishment, and repair processes"*.

Introduction

Electrical and electronic equipment (EEE) constitute a major proportion of e-waste (Ghosh *et al*., 2020). These appliances have become an integral part of human life as a symbol of extravagance and a higher standard of living. Most recent turns of events and innovative upgradations in the technology decrease the expense of electric and electronic equipment prompt their higher utilization, and in this manner extending the electronic market at a higher rate (Pavithra *et al*., 2020). Notwithstanding, the assortment and recycling of electronic waste happen at a moderate pace when contrasted with its production which thus causes natural concerns (Awasthi *et al*., 2016). e-waste is a worldwide ecological issue that especially influences the natural ecosystem through its harmful synthetic substances that leached out in the distinctive natural environmental spheres in small fractions and hence initiate toxic impacts in the earth's ecosystems (Vaish *et al*., 2020). Scientific management of e-waste is kept on being a test in the present situation. In this manner to handle the persevering issue, different physical and chemical modes have been adopted (Kaya, 2016). Since these advancements are profoundly proficient for e-waste management and source recuperation, they are known for their higher energy utilization and operational expense. Despite these, bioleaching offers a characteristic, natural, and cost-benefit organic methodology for e-waste management and recuperation of valuable metals present in it using a variety of bacterial and fungal species. The bioleaching productively oversees electronic waste and recoup valuable metals present in e-waste scrap with minimal ecological harms.

This chapter emphasized the types of microorganisms and their performance in metal bioleaching and inspects the bioleaching of gold, iron, and copper from e-waste scrap. Additionally, health and environmental impacts are also discussed.

Statics on e-waste generation

The consistently expanding quantum of e-waste is booming at an extremely high pace which is around 20-25 Mt for every year (Mihai, 2016). As indicated by the GEWM report (2020), the absolute e-waste generated in 2019 is assessed to be 53.6 million metric tons over the globe which was configured to 7.3 kg per capita generation. The scientists anticipated that the absolute e-waste will ascend to 74 Mt in 2030. Aside from generation, the documented collection and recycling of e-waste was found to be 9.3 Mt which was merely a total fraction of 17.4% when compared to the total waste generated (Forti *et al.*, 2020). The amount of e-waste in the year 2019 involved various Categories as appeared in Table 1. In the case of Asia, this report gauges 24.9 Mt (5.6 kg per capita) generation of e-waste while just 11.7% of it is appropriately collected and recycled (Forti *et al.*, 2020).

Bioleaching pathways

Bioleaching includes biochemical systems of bacterial and fungal strains for proficient metal recuperation from e-waste. The procedure utilizes their metabolic byproducts and enzymatic activities. There are two fundamental modes of bioleaching pathways as described below:

Direct

This pathway includes the process of metal oxidation with the assistance of enzymatic responses started by explicit microorganisms (Bal *et al.*, 2019; Zhao and Wang, 2019). In this procedure, the electronic waste is presented at the inoculation stage by the addition of metabolic acids in a single stage and two-way stages (Arya and Kumar, 2020; Baniasadi *et al.*, 2020). For instance, certain microbes like *Thiobacillus ferrooxidans*, which are profoundly acidophilic and gram-negative aides in the oxidation of Fe^{2+} to Fe^{3+} and in this way acquired vitality for their metabolic capacities (Miao *et al.*, 2017). Reactions are delineated below:

$$4\ FeSO_4 + 2\ H_2SO_4 + O_2 \longrightarrow 2\ Fe(SO_4)_3 + 2\ H_2O$$

$$2\ S^0 + 3\ O_2 + 2\ H_2O \longrightarrow 2\ H_2SO_4$$

$$2\ FeS_2 + 7O_2 + 2\ H_2O + 2\ H_2SO_4 \longrightarrow 2\ FeSO_4 + 2\ H_2SO_4$$

Table 1. Different categories of equipment's that produces e-waste (Forti *et al.*, 2020).

Categories of equipment's	Quantity (Mt)
Smaller equipment's	17.4
Large electronic equipment	13.1
Electronic temperature exchange equipment	10.8
Monitors and Screens	6.7
IT and telecommunication equipment's	4.7
Lamps, bulbs	0.9

Indirect

This pathway is a two-way process where microorganisms don't legitimately include in the mineralization of metals yet they generate solid oxidizing agents. For example, ferric ions and sulfuric acid that cooperate with metals and balance out them in a profoundly acidic medium. The oxidation of Fe, S, and distinctive metal sulfides assumes their significant role in keeping up acidic conditions fundamental for mental disintegration (Sajjad *et al*., 2019; Sand, Gehrke *et al*., 2001). The mechanism of copper bioleaching is represented in Figure 1. Bioleaching includes the use of biological agents for e-waste metal recovery. They transform the metals present in the electronic waste scrap (Pant *et al*., 2018). The biochemistry involved in bioleaching is presented in Table 2.

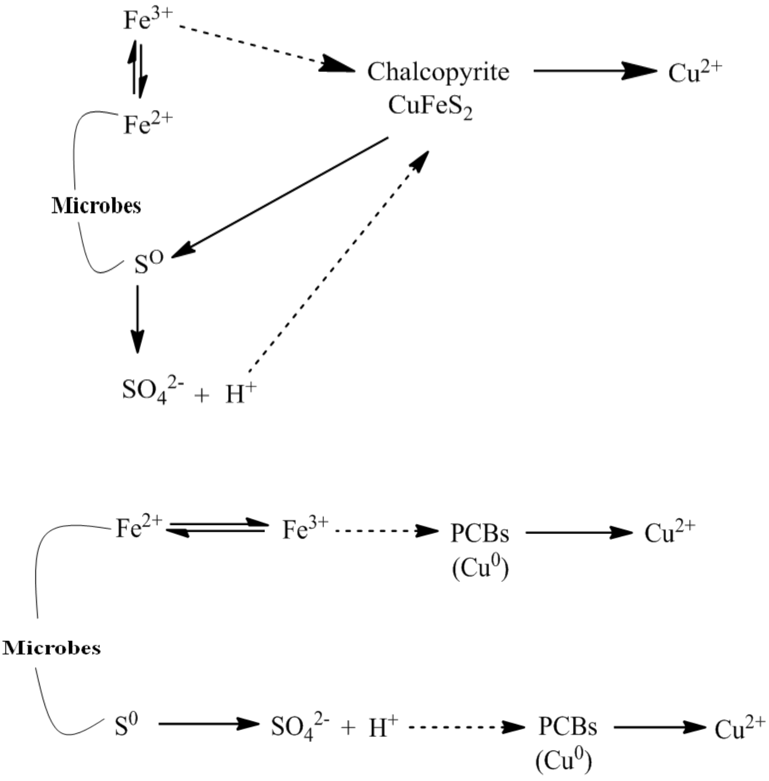

Figure 1. Indirect bioleaching pathway of copper bioleaching from chalcopyrite and PCBs (Source: Zhao and Wang, 2019).

Table 2. Biochemistry involved in biological leaching of various metal ions.

Reagents	Leached metals	Microbes involved	Biochemistry	References
HCl, HNO_3, H_2SO_4, Aqua regia	Co, Li	*Aspergillus niger, Acidithiobacillus thiooxidans*	$Co^{2+}+Na_2S \rightarrow CoS_{(S)}+2Na^+_{(aq)}$ $Co^{2+}_{(aq)}+2NaOH \rightarrow Co(OH)_{2(s)}+2Na^+$ $Co^{2+}_{(aq)}+Na_2C_2O_4+2H_2O \rightarrow CoC_2O_4.2H_2O_{(s)} +2Na^+_{(aq)}$ $2Li^+_{(aq)}+ Na_2Co_3 \rightarrow Li_2Co_{3(s)}+2Na^+_{(aq)}$	Biswal *et al.* (2018)
Aqua regia, Concentrated HF	Mn, Al, Zn, Cu, Ti	*Thiobacillus ferrooxidans*	$ZnS + 2Fe^{3+} \rightarrow Zn^{2+} + 2Fe^{2+} + S^0$ $ZnS + 2O_2 \rightarrow Zn^{2+} + SO_4^{2-}$ $4Fe^{2+} + O_2 + 4H^+ \rightarrow 4Fe^{3+} + 2H_2O$	Arshadi *et al.* (2020)
KCl, K_2HPO_4, $(NH_4)_2SO_4$	Fe	Thermophilic culture	$Fe_7S_8+7FeSo_4 \rightarrow 7FeSo_4+7H_2S+S$ $Fe_7S_8+H_2O+15.5O_2(g) \rightarrow 7FeSo_4+H_2SO_4$ $Fe_7S_8+O_2(g) \rightarrow 7FeSo_4+ S$ $Fe_7S_8+31Fe_2(SO_4)_3+32H_2O \rightarrow 69\ Fe(So_4) +32H_2SO_4$ $Fe_7S_8+7Fe_2(SO_4)_3 \rightarrow 21FeSO_4+8S^0$	Altinkaya *et al.* (2018)
Inorganic Sulfuric acid	Cu	*Acidithiobacillus thiooxidans*	$S^0+1.5\ O_2+H_2O \rightarrow 2H^++SO_4^{2-}$ $Cu \rightarrow Cu^++e^-$ $Cu^+ \rightarrow Cu^{2+}+e^-$ $O_2+4H^++4\ e^- \rightarrow 2H_2O$ $2Cu^++O2+4H^+ \rightarrow 4Cu^{2+}+2H_2O$ $Cu^{2+}+SO_4^{2-} \rightarrow CuSO_4$	Hong and Vali (2014)
Sulfuric acid	Cu, Al, Zn, Ni	*Thermoplasma acidophilum*	$Cu^0+Fe_2(SO_4)_3 \rightarrow CuSO_4+2FeSO_4$ $Zn^0+ Fe_2(SO_4)_3 \rightarrow ZnSO_4+2FeSO_4$ $Ni^0+ Fe_2(SO_4)_3 \rightarrow NiSO_4+2FeSO_4$ $2Al^0+3Fe_2(SO_4)_3 \rightarrow Al2(SO_4)_3+6FeSO_4$	Ilyas *et al.* (2007)
Cyanide	Au	*Chromobacterium violaceum*	$FeS_2+6Fe^{3+}+3H_2O \rightarrow S_2O_3^{2-}+7Fe^{2+}+6H^+$ $S_2O_3^{2-}+2O_2+H_2O \rightarrow 2SO_4^{2-}+2H^+$ $S_2O_3^{2-}+4Fe^{3+}+5H_2O \rightarrow 2SO_4^{2-}+4Fe^{2+}+10H^+$ $2Fe^{2+}+2H^++0.5O_2 \rightarrow 2Fe^{3+}+H_2O$ $UO_2+2Fe^{3+} \rightarrow UO_2^{2+}+2Fe^{2+}$ $4Au+8CN^-+O_2+2H_2O \rightarrow 4Au(CN)_2^-+4OH^-$	Nancharaiah *et al.* (2016)
Sulfur	Fe	*Acidithiobacillus*	$6Fe^{3+}+S^o+4H_2O \rightarrow 6Fe^{2+}+SO4^{2-}+8H^+$ $6FeO.OH+S^o+10H^+ \rightarrow 6Fe^{2+}+SO4^{2-}+8H_2O$	

Mechanisms of metals bioleaching

Gold bioleaching

Gold bioleaching gives a significant and alluring exploration research area including innovative progression in gold recovery from electronic waste. The mesophilic, facultative, and gram-negative microbe *Chromobacterium violaceum* (Pant and Sharma, 2015) gives a chance to recoup the gold from printed circuit boards of the waste gadgets (Li *et al.*, Ma, 2015). This specific microorganism generates CN^- that may help in gold solubilization in the acidic medium in this way helps in gold bioleaching in an effective manner (Chi *et al.*, 2011). The mechanism of gold bioleaching (Liu *et al.*, 2016) is summarized in the following chemical reactions:

$$4Au + 8CN^- \longrightarrow 4Au(CN)^-_2 + 4e^-$$

$$O_2 + 2H_2O + 4e^- \longrightarrow 4OH^-$$

$$4Au + 8CN^- + O_2 + 2H_2O \xrightarrow{\textit{Chromobacterium violaceum}} 4Au(CN)^-_2 + 4OH^-$$

Various investigations have been done on in a similar field to get upgraded recuperation rates of gold (Willner and Fornalczyk, 2013). Aside from *Chromobacterium violaceum*, researchers also utilize *Pseudomonas balearica* SAEI strain for gold bioleaching and a recuperation rate of 68.5% has been observed (Kumar *et al.*, 2018). Also, another specialist utilizes the organism *Aspergillus niger* of the family *Trichocomaceae* for gold bioleaching and 56% of the recuperation rate has been accomplished (Argumedo-Delira *et al.*, 2019; Becci *et al.*, 2020). The flow chart of gold bioleaching (Figure 2) using *Aspergillus niger* from printed circuit boards is given below:

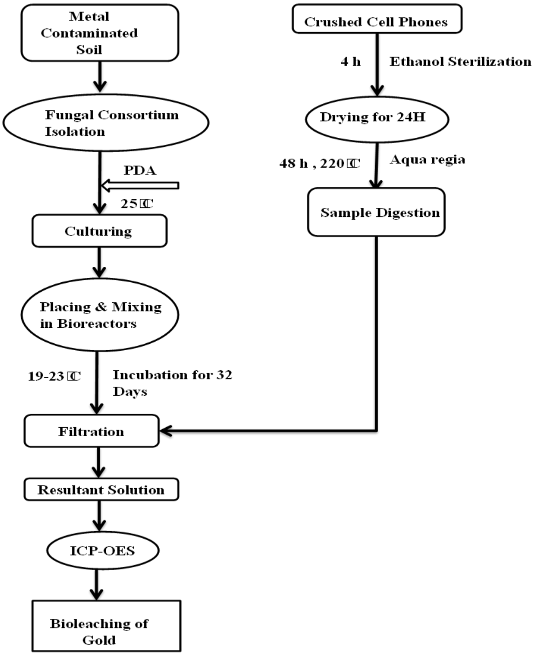

Figure 2. Gold (Au) bioleaching from printed circuit boards of mobile phones using *Aspergillus niger* (Argumedo-Delira *et al*., 2019).

Iron bioleaching

Iron is bleached by acidophilic microbial species including the cooperation of ferric ions with H_2SO_4 either by thiosulfate or polysulfide pathways (Figure 3) and in this way metal solubilization occurs. These bacteria can contact with iron and oxidize the Fe^{2+} ions to Fe^{3+} and reduces sulfur to $S_2O_3^{2-}$. For example, *Acidithiobacillus ferrooxidans* bacteria attacks iron and initiate extracellular enzymatic actions (Maluckov, 2017; Saavedra *et al*., 2020). Oxidation of Fe^{3+} to Fe^{2+} ions happened due to electron transfer (Drits and Manceau, 2000). At the outer membrane of bacteria, Fe^{2+} ions are reoxidized to Fe^{3+} ions (Geerlings *et al*., 2019). The thiosulfate oxidation mechanism (Masau, 1999) is represented in the following generalized equations:

$$FeS_2 + 3.5O_2 + H_2O \longrightarrow Fe^{2+} + 2SO_4^{2-} + 2H^+$$

$$MeS + 2Fe^{3+} + 1.5O_2 + H_2O \longrightarrow Me^{2+} + 2Fe^{2+} + SO_4^{2-} + 2H^-$$

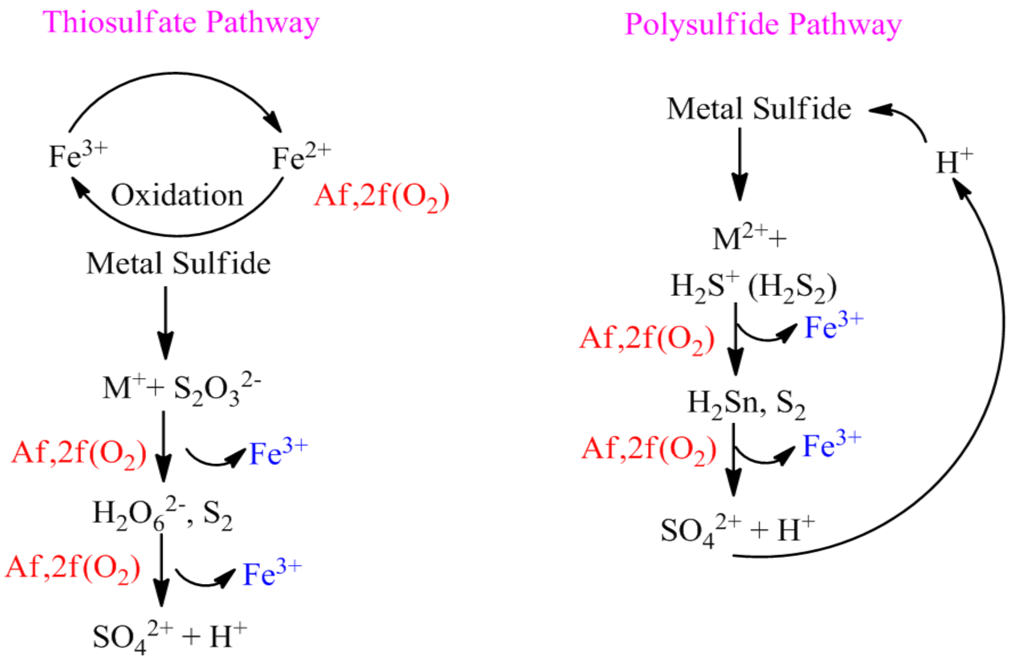

Figure 3. Mechanism of iron bioleaching involving thiosulfate or polysulfide pathways (Pant *et al*., 2018; Srichandan *et al*., 2020).

Copper bioleaching

The copper dissolution from e-waste generally occurs in two main phases. The first phase involves the oxidation of the ferrous ion to ferric ions with the help of bacteria and the second phase involves the copper mobilization from the e-waste scrap which is induced by the ferric ion's reduction to ferrous ions. In this way, the continuous cycle between ferric and ferrous ions is going on and the copper metal is bleached from the electronic waste (Wu *et al*., 2018). The copper bioleaching chemical reactions are given ahead:

$$Fe^{2+} + O_2 + 4H^+ \xrightarrow[\textit{Acidithiobacillus thiooxidans}]{\text{Microbes}} Fe^{3+} + 2H_2O$$

$$2Fe^{3+} + Cu \longrightarrow 2Fe^{2+} + Cu^{2+}$$

Environmental consequences and health impacts

A few investigations attempt to audit the toxic impacts of e-waste on people just as on various ecological environmental spheres. Investigations are referencing its natural concerns and related effects. The use of unscientific e-waste management practices like melting, roasting, open-air burning and so forth generate toxic dioxins and other air born hazardous chemicals that may have direct ecological concerns and health-related issues. Table 3 shows different environmental and health impacts that are associated with e-waste.

Table 3. List of environmental and health impacts of hazardous constituents present in e-waste.

E-Waste Sources	Constituents	Consequences	Health impacts	References
Mercury vapor lamp PCBs Relay, Board switches	Mercury vapors Mercury Mercury	-Bioaccumulation causes higher level of toxicity in aquatic animals. e.g. fish, seabirds, etc. -Dry deposition in air causes air pollution. -Ground level interactions with ozone.	-Neuronal dysfunction. -Insomnia -Distorted vision. -Muscle weakness. -Blood poisoning. -Disturbed sensations. -memory loss.	Ha *et al*. (2017); Lindqvist (1995); Sarikaya *et al*. (2010); Wang *et al*. (2020); Wang *et al*. (2019)
Housing wiring	BFR	-Affect air quality of e-waste dismantling facility. -Contaminate the soil through their sedimentations with soil particles. -Bioaccumulation within the food chain.	-Cancer. -Diabetes. -Neurological concerns. -Reproductive and developmental abnormalities.	Kim *et al*. (2014); Segev *et al*. (2009); Yu *et al*. (2016)

Table 3. *Continued...*

E-Waste Sources	**Constituents**	**Consequences**	**Health impacts**	**References**
Circuit Breakers	SF_6	-High level of global warming potential as compared to carbon dioxide and methane. -Highly persistent in nature. -On its decomposition, it generates highly toxic Di-sulfur decafluoride. -Highly persistent in nature.	-Damaged hepatic and renal organ systems. -Suffocation. -Nasal and bronchitis congestion. -Extensive lung damage. -Respiratory problems. -Dizziness and fainting.	Blackburn and Solutions (2017); Dervos and Vassiliou (2000); Tsai (2007)
CRTs	Barium, Lead	-Contaminate underground water sources on mixing when leaked from shale gas wells. -Ba is long term stable in the environment. -Lead from anthropogenic sources enters in the soil and water therefore, causes soil, water pollution.	-High blood pressure. -Respiratory problems. -Cardiovascular and kidney disease. -Behavioral changes. -Altered metabolism. -Neurological and mental illness. -Anemia. -Nervous system disorders in babies, -Abnormal enzymatic system of the body.	Kravchenko *et al*. (2014); Lecler *et al*., (2015); Wani (2015); Xu *et al*. (2013)
Plastic of Keyboards, Monitors etc.	Brominated dioxins and Hydrocarbons	-Brominated dioxins are highly persistent environmental pollutants. -Increases total toxicity of environment. -Hydrocarbons contribute in global warming and green house effect.	-Affect neuronal development. -Irregular heart beat. -Coma. -Prostate cancer.	Birnbaum *et al*. (2003); Ince and Ince (2019); Tue *et al*. (2013)
Mobile battery	Lithium and Nickel	-Lithium leaching affects soil and water systems. -Toxic effects of lithium causes river water pollution and wildlife destruction. -Nickel adversely affects the environment. -Nickel promotes GHG emissions, habitat loss and air, water, soil pollution.	-Burning sensation. -Cough. -Skin rashes and redness. -Vomiting. -Abnormal lung activity. -Chronic bronchitis. -Lung cancer. -Dermatitis.	Gaines and Dunn (2014); Genchi *et al*. (2020); Hedya *et al*. (2019); Nakajima *et al*. (2017)

Table 3. *Continued*...

E-waste Sources	Constituents	Consequences	Health Impacts	References
Semiconductors and Chip resistor	Cadmium	-Highly persistent toxicant. -Industrial activities like smelting and reclamation raise cadmium concentration in the air.	-Deformed brain development. -Cancer. -Emphysema. -Chronic obstructive pulmonary disease. -Renal and Cardiovascular ailments.	Dhiman (2020); Dökmeci *et al*. (2009); Fleischer *et al*. (1974); Hayat *et al*. (2019)

Conclusion

Bioleaching is a simple and exceptionally successful innovative technology for metal extraction from e-waste scrap and its scientific management. Aside from metal recovery, this technique likewise gives remedial measures to the detoxification of wastewater, mechanical waste, heavy metals, and sewage sludge. Organisms assume their significant role in the biogeochemical cycling and productive extraction of metals from electronic waste. The inclusion of organisms modifies the procedure of metal extraction when compared with the ordinary metal extraction procedures of pyro and hydrometallurgy. Nonetheless, a few confinements like inconsistent and low recovery yield, slow procedure, risk of contamination have been distinguished as the genuine problems with this process. Therefore, additional research is needed to modify the existing bioleaching process for higher metal recovery rates from electronic waste scrap.

Conflict of interest: The authors declare no conflict of interest.

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