

Environmentally sound system for E-waste: Biotechnological perspectives

Abhishek Kumar Awasthi^a, Mohammed Hasan^b, Yogendra Kumar Mishra^{c,*}, Akhilesh Kumar Pandey^d, Bhupendra Nath Tiwary^e, Ramesh C. Kuhad^f, Vijai Kumar Gupta^{b,*}, Vijay Kumar Thakur^{g,*}

^a School of Environment, Tsinghua University, Beijing 100084, China

^b Department of Chemistry and Biotechnology, Tallinn University of Technology, 12618 Tallinn, Estonia

^c Mads Clausen Institute, NanoSYD, University of Southern Denmark, Alsion 2, 6400 Sønderborg, Denmark

^d Department of Biological Sciences, Rani Durgavati University, Jabalpur (M.P.), India

^e Department of Biotechnology, Guru Ghasidas Vishwavidyalaya (Central University), Bilaspur, Chhattisgarh, India

^f Central University of Haryana, Mahendragarh, Haryana 123031, India

^g Enhanced Composites and Structures Center, School of Aerospace, Transport and Manufacturing, Cranfield University, Bedfordshire MK43 0AL, UK

ARTICLE INFO

Article history:

Received 23 July 2019

Received in revised form 19 October 2019

Accepted 21 October 2019

Available online xxxx

Keywords:

E-waste

Environmental problem

Public health

Metals

Biotechnology

ABSTRACT

The rapid e-waste volume is generating globally. At the same time, different recycling technologies, mainly the mechanical and chemical methods well studied, while the biological method is the most promising approach. Therefore, this article provides a comprehensive information about extracting valuable metals from e-waste. In addition, this article outlines the process and key opportunity for extraction of metals, identifies some of the most critical challenges for e-waste environmentally sound management practices, and opinions on possible solutions for exiting challenges, and emphasis on importance of advanced recycling technologies that can be utilized, in order to minimize the environmental impact causes due to improper recycling of e-waste.

1. Introduction

The high quantity of electrical and electronic products is rapidly becoming a waste stream around the globe (Awasthi et al., 2019; Awasthi and Li, 2017a, 2017b). According to United Nation University (UNU) report estimated that, the total 44.7 million metric tonnes (Mt) e-waste generated worldwide in 2016, furthermore predicted that, the total quantity of e-waste to be increased up to 52.2 Mt. (or 6.8 kg/inh) by 2021; out of the total e-waste generated, just 20% e-waste officially collected and recycled formally (Baldé et al., 2017). There are reports (Huisman et al., 2015; Odeyingb et al., 2017) suggested that, many developed countries, send their e-waste to the several other countries such as, Malaysia, Thailand, Nigeria, Ghana, Indonesia (Wong et al., 2007), however, once these countries stop this and the e-waste recycling is going to be a new and open challenge for several well-developed countries. In fact, e-waste management is not being well regulated, particularly in many developing countries (Awasthi et al., 2016; Duan et al., 2016; Li et al., 2015a, 2015b; Sthiannopkao and Wong, 2013). As a result, improper recycling

practices have become very common in developing countries, which leads to release- of hazardous materials/substances including's heavy metals, such as Cu, Cd, Cr, Pb and Hg along with polychlorinated biphenyls, polychlorinated diphenyl ethers, polychlorinated dibenzo-*p*-dioxins and dibenzofurans into the environment, which may cause negative impacts to the environment and public health (Awasthi et al., 2016, 2019; Song and Li, 2014).

While on the other hand, this e-waste could be considered as a secondary resource, since it contains valuable metals [copper, gold, and Rare Earth Elements (REEs) i.e., Neodymium (Nd), Indium (In), Yttrium (Y), Gallium (Ga)] (Awasthi et al., 2019; Maneesuwannarat et al., 2016; Pourhossein and Mousavi, 2018; Vats and Singh, 2015). For almost two decades, e-waste being recycled mainly by using technologies, such as mechanical process, and chemical leaching techniques (Awasthi et al., 2016; Awasthi and Li, 2017a, 2017b; Kaya, 2016; Pant and Singh, 2013). However, these recycling process have obvious limitations, for example, mechanical process needs at least capital cost investment, while the hydrometallurgy method consumes chemicals, these chemical process may cause secondary pollution to the environment, while the pyrometallurgy method requires high energy inputs which makes them comparatively costly (Arshadi and Mousavi, 2014; Baniasadi et al., 2019; Hong and Valix, 2014; Rozas et al., 2019). Despite the fact, biotechnological methods involving a different

* Corresponding authors.

E-mail addresses: mishra@mci.sdu.dk (Y.K. Mishra), vijai.gupta@taltech.ee (V.K. Gupta), vijay.kumar@cranfield.ac.uk (V.K. Thakur).

mechanism for removal of critical metals from e-waste (Brandl et al., 2001, 2008; Awasthi and Li, 2017a, 2017b; Senophiyah-Mary et al., 2018), yet have demonstrated better efficiency of the process. Therefore, the main objective of this article is to present outlook on environment-friendly processes in order to recover valuable resource materials & metals from e-waste.

2. Resources in E-waste

E-waste contains significant portion of metallic about 60% (Widmer et al., 2005), which includes both precious & heavy metals and Rare Earth Elements (REEs) (Al-Ghouti et al., 2016; Awasthi et al., 2018; Wang et al., 2012; Won et al., 2014). Besides, researchers have estimated that the metals, such as copper, tin and zinc requirement demand would be increased in next coming years (Meylan and Reck, 2017; Tansel, 2017; Yang et al., 2018). Also, the REEs are in a high supply risk for renewable energy production (Cucchiella et al., 2015; Henckens et al., 2014). For example, the e-waste lithium-ion batteries can be a potential resource to fulfill future demand and support the supply chain to maintain cobalt sustainability (Zeng and Li, 2015). In other word, e-waste contains a significant amount of valuable metals than ores mining (Zeng et al., 2018; Yang et al., 2018).

The technology advancement to improve daily life and routine working style also led to the development of several electricals and electronic equipment for frequent use in all areas. Each of these appliances has some lifetime, after which they do not remain in a proper (usable) condition of its primary intended function with satisfactory performance and needs to be discarded as e-waste. Considering this issue, its impact and to create awareness about collecting and recycling e-waste, the first international e-waste day was celebrated on 13th October 2018 in Europe and other major countries through WEEE [European Association of Electrical and Electronic Waste Take-Back Systems] forum. [<https://www.weee-forum.org/international-e-waste-day-0>].

The global material extraction has been estimated to increase with 10 fold from 7 billion tonnes in 1900 to 68 billion tonnes in 2009. The second-biggest increase was found to be the ores and industrial minerals extraction with 31 times enhancement compared to 1900 levels, where the first being materials extraction for construction with 40-time enhancement (Hunt et al., 2013). Since, all the elements in the periodic table have limited existence on the earth, which ranges from the finite amount to abundance nature (iron, aluminum and silicon) for individual elements. Considering the current rate of extraction and annual production rate, several elements primary (virgin) reserves are expected to disappear within 50 years which includes elements such as; Mn, Zn, Ga, Ge, As, Sr, Ru, Rh, Ag, Cd, In, Sn, Sb, Hf, W, Os, Ir, Pt, Au, Tl, Bi (Brown et al., 2013; Salazar, 2013). Further, the low crustal abundances of few elements make them at high risk including examples of manganese (Mn) and strontium (Sr). Similarly, the case of element indium is even more alarming (Song et al., 2020; Swain and Lee, 2019), which is frequently used in solar cells, semiconductors and display devices, and it is expected to run out in within 13 years based on current use and production. In such a situation, the secondary sources of urban mining will become critical. While, For example, if we simply consider the mobile phone production data of 2008, where approximately 1300 million mobiles were produced worldwide, which utilized palladium (12 tons), gold (31 tons), silver (325 tons), cobalt (4900 tons) and copper (12,000 tons) and most of it by 2018 should have become E-waste and might have been stated as key resource (Hunt et al., 2013; Meskers, 2009).

The most critical elements include; such as indium, niobium, antimony, gallium, platinum group metals (PGM), and other REEs are at high risk of supply. Many times, international geographical situation could also affect the supply of metals, because geographically not equally distributed worldwide. For example, the Democratic Republic of Congo (DRC) supplies 40% of the world's cobalt, whereas South Africa delivers 89% of the world's PGM. Similarly, Brazil is the almost a specific producer of niobium with 90% of the world production, makes international scenarios, directly

affecting the ease of supply of metals to the world. Considering the present and future environmental issues, the idea of clean, green, and sustainable methods of obtaining/recovering chemical(s) from the primary natural resources and secondary man-made resources including e-waste with efficient, economical, environmentally friendly methods, has become a hot topic of research (Kaya, 2016; Nakamura and Halada, 2015).

3. Potential of advance recycling technology for metal recovery from e-waste

Several conventional technologies (including both mechanical and chemical methods) have been used for metal extraction from e-waste. However, such technologies are either highly costly or can pose secondary pollution, which needs further treatment, while the biological approach is environment-friendly for metal recycling from e-wastes. Therefore, this section of the article briefly discusses the potential of biological methods for recycling/removing metals from e-waste.

3.1. Environmentally sound approach

Among several recycling technologies for metal extraction from e-waste, the microbial technology is catching high attention in the recent scientific investigation (Jujun et al., 2014; Kaksonen et al., 2018; Sahni et al., 2016; Sun et al., 2016). In the microbial technology, microbes play an important role in the leaching of metal into liquid form (Sun et al., 2016; Heydarian et al., 2018). For example, Horeh et al. (2018) suggested that the environmentally sound extraction of metals from spent lithium-ion batteries, this could be advantageous in terms of economic and environmental perspective. Additionally, study also suggested, the adopted *Aspergillus niger* produce organic acids (e.g., citric, gluconic, oxalic and malic acid) could act as active chelating agents in the biohydrometallurgical process for recovering metals from spent lithium-ion batteries. Specially, the study reported that, the adapted *Aspergillus niger* produced gluconic acid, which was main chelating agents with ability to dissolve 100% of Li, 94% of Cu, 72% of Mn, 62% of Al, 45% of Ni, and 38% of Co, at the pulp density of 1% (w/v). Similarly, for instance, Xia et al. (2018a, 2018b) used an indigenous fungal strain to produce organic acids in biohydrometallurgy process, for metal recycling from waste Printed Circuit board (PCB). They reported that among studied three bioleaching methods; (i) One-step, (ii) Two-step, and (iii) Spent medium methods., the spent medium process exhibited as the best method to remove copper from the pulp density of waste PCBs. Sahni et al. (2016) research suggested uses (microorganism such as *Chromobacterium violaceum*) of chemo-biohydrometallurgy approach for extraction of metals from obsolete SIM card (e-waste). However, they achieved a lower recovery rate, 13.79% of copper, 2.55% of silver, and 0.44% of gold of untreated SIM waste, while about 72% of copper mobilized from SIM e-waste, by using acidic pretreatment of SIM e-waste in two-step bioleaching (Sheel and Pant, 2018; Xia et al., 2018a, 2018b). So, these are the perfect examples that indicate that a biohydrometallurgical method is one of the promising biotechnological approaches for metal extraction from e-waste (Kaksonen et al., 2018; Lewis et al., 2011). In this context, in recent years, a number of scientific studies define the potential of bioleaching methods for the extraction of valuable metals from e-waste (Arshadi and Mousavi, 2015; Arshadi et al., 2016; Chi et al., 2011; Xin et al., 2012; Heydarian et al., 2018; Horeh et al., 2018; Kim et al., 2016; Niu et al., 2015; Sun et al., 2016). The optimal condition for bioleaching of Cu, Mn and Zn from powdered spent batteries by using mixed culture (*Acidithiobacillus thiooxidans* and *Leptospirillum ferriphilum*) has been reported by Niu et al. (2015). A number of known bacterial strains have displayed the capability for dissolution of metals (Arshadi and Mousavi, 2015; Arshadi et al., 2016; 2019; Heydarian et al., 2018). Although, it is assumed that diverse microorganisms have their own specific mechanisms for metal bioleaching. Wu et al. (2018) demonstrated that, after 2 h of the time period, almost 100% of copper recovery from 5 g/L PCBs. Their findings further suggested bacterial

bio-oxidation activity significantly inhibited, possibly owing to the toxicity of waste PCBs.

REEs have been often used in various electronics manufacturing. As a bioleaching process using heterotrophic bacteria (such as; *Cellulosimicrobium funkei*) is a promising method for gallium arsenide (GaAs) leaching from a semiconductor (Maneesuwannarat et al., 2016). Similarly, one of the examples is the recovery of REEs from fluorescent powder, by using the tea fungus Kombucha (Hopfe et al., 2017; Marsh et al., 2014). Jowkar et al. (2018) reported the 100% recovery of Indium (In) and while less (10%) for Strontium (Sr) at optimized conditions. Additionally, the findings also suggested that Indium metal bioleaching from discarded liquid crystal displays (LCD) was more effective and eco-friendly than the chemical leaching process (Fathollahzadeh et al., 2018). In the latest publication, the researcher used fungus *Aspergillus niger* for bioleaching of Yttrium (Y) from shredding dust of e-waste (Marra et al., 2018), and their research suggested that by avoiding the shredding dust does not end up into open lands, while the extraction of valued metals and other components & materials needs to fulfill the requirement of the metal resource. Marra et al. (2018) developed a process for the extraction of valuable metals including REEs from dust generated owing to shredding practices recycling e-waste. In the first step, cerium, europium, and neodymium were leached at high percentages (>99%), while yttrium and lanthanum removed about 80% from the shredded dust after 8 days by using bacterial strain *Acidithiobacillus thiooxidans* (DSM 9463), whereas in the second stage, the bacterial strain *Pseudomonas putida* (WSC361) produced cyanide able to dissolved 48% of Au (*A. thiooxidans* leached shredding dust), after the 3 h of incubation period (Johnson, 2014).

In simple meaning, biological approach such as, biosorption is a process that permits the binding among the concentration of different metal ions from an aqueous solution through microbial biomass or their metabolites (Sheel and Pant, 2018). The biosorption method is principally useful for the leaching and recovery of valuable metals (platinum, palladium, and gold) from the liquid containing waste PCBs (Brandl et al., 2008; Ma et al., 2006; Sheel and Pant, 2018). However, there are most important tasks in these techniques are total metal-binding capacity, selectivity, the stability of materials, renewability materials as well as cost-efficiency. In this context, number of studies focused on the application of fungi, bacteria, yeast and agricultural waste (eg., ground nutshells, plant residues) as a biosorption material (Bindschedler et al., 2017; Diniz and Volesky, 2005; Sheel and Pant, 2018; Hassan et al., 2018; Fomina and Gadd, 2014; Gadd, 2009; Khoo and Ting, 2001; Naseem Akhtar et al., 1995; Ting and Mittal, 2002; Vendruscolo et al., 2017). Furthermore, the recent research & developments in bioengineering, improvement in microbes, and mutant enzymes, e.g., metal-binding peptides, expression of metallothioneins or new metal-binding proteins and their potential of cell surfaces. A potential eco-friendly approach is the utilization of metal-binding peptides through a phage surface display. Through this method, the specific peptides for metal ions or metallic surfaces were selected by Wang and Chen (2009); and Pollmann et al. (2018). Another, the bioelectrochemical method (Nancharaiah et al., 2015), which is also a promising modern biotechnology approach for critical metal recovery from e-waste, and the residual wastes of e-waste. In this aspect, Nancharaiah et al. (2016) article is the state of art research of bioelectrochemical systems for removal/recovery of metal(loid) ions and pertaining removal mechanisms. Hennebel et al. (2017) presented a brief overview of R&D priorities, and future perspectives described biotechnology application for critical metals recycling from the available resource.

4. General discussion

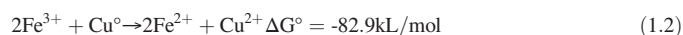
The biotechnology approach is defined as the application of the potential microorganisms to remove or transform the pollutants to less-hazardous or non-hazardous form in the environment by the microbial metabolisms. There are different mechanisms in microbial remediation of metals; such as (a) Biotransformation; (b) Biosorption; (c) Bioaccumulation; (d); Bioleaching and (e) Biomineralization. Microorganism's ability plays

significant roles in metabolizing pollutants including's metals, which is one of the key contaminants in e-waste contaminated soils. The diversity of most microbial taxa can vary with heavy metal concentration levels to a diverse extent (Jiang et al., 2019).

4.1. Biotechnology mechanisms, microorganism's role of chelating agents involved in metal solubilisation process for e-waste recycling

The bacterial strain of *At. ferrooxidans* has been a purpose of specific interest, due to its extraordinarily extensive metabolic ability, it can grow aerobically either reduced inorganic sulphur compounds to elemental sulphur or on the oxidation of iron(II), however during the anaerobic process of growth is likely through the oxidation of sulphur or hydrogen coupled with iron(III) reduction (Podar and Reysenbach, 2006; Zhuang et al., 2015). The other bacterial species such as *Acidithiobacillus* can also oxidise sulphur, however, it cannot oxidise iron. While, the iron oxidisers, such as mesophilic microorganisms are mostly associated with the bacterial species, such as *L. ferrooxidans*, *L. ferriphilum* (*Leptospirillum* genus). The sulphur oxidisers (moderate thermophiles) are belongs to gram-positive, such as *Sulfobacillus* and *Alicyclobacillus*, whereas iron oxidisers are belonged to Actinobacteria, for instance; *Ferrimicrobium*, *Ferritrix*, and *Acidimicrobium*. The thermophile microbial group is belonging to those strains relating to sulphur-oxidising archaea (archaea domain). As best of our knowledge, very limited studies has been done on the thermophile microbial group, while there are number of archaea bacteria recognized to be involved in the oxidation of mineral sulphides (Zhuang et al., 2015; Yang et al., 2014; Yang et al., 2017a; Banerjee et al., 2017; More et al., 2014).

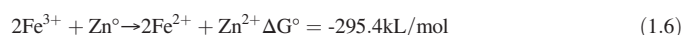
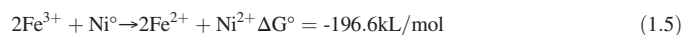
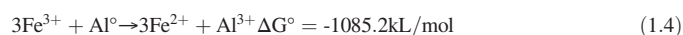
The authors suggested possible reactions explaining the key mechanisms of copper metal bioleaching from waste PCBs (Xiang et al., 2010; Wang et al., 2009). In the occurrence of iron considering as the potential energy source for bioleaching microbial strains, the bio-oxidation of Fe(II), and resulted produces Fe(III), which is accountable for the oxidation of insoluble form of Cu⁰ into the soluble form of Cu²⁺, referring to Eqs. 1.1 and 1.2:



Cu leaching was detected, while iron absent, and elemental sulphur used as the source of energy. This means the protons is responsible for solubilised part of zero-valence copper, even though in these conditions, the molecular oxygen is involved:



In the course of the dissolution of copper, Fe(III) ions are significantly free from the PCB metallic component; and Fe(III) ions will take part in the reaction (Eq. 1.2), hydrolysis producing new protons, and increase copper solubilisation as showing in Eq. 1.3. The solubilisation of metals, such as "Al, Ni, and Zn" would be depending on the mechanisms according to their thermodynamic reactions (Eq. 1.4–1.6):



Some examples of these studies are presented in Table 1, along with some more recent studies, covering a wider range of elements (REEs), and critical metals. The linked research reveals a high innovation potential and a variety of research strategies for biomining. These methods achieved significantly higher leaching. While on the other hand, it is essential to maintain the acidification environment in growth media in order to

Table 1
Studies based on biological approaches for metal removal from E-waste.

Microorganisms	Experimental condition	Leached metals % (mg/g PCB)	References
<i>Pseudomonas putida</i> (two-step)	Temperature: 30 °C; pH: 8.0–9.2	Cu: 98% (164 mg/g), Au: 44% (0.1 mg/g)	Işıldar et al., 2016
<i>Acidithiobacillus ferrooxidans</i>	Temperature: 30 °C, pH: 2.0	Cu: 95% (203 mg/g)	Chen et al., 2015
<i>Sulfobacillus thermosulfidooxidans</i>	Temperature: 45 °C, pH: 2.0	Cu: 95% (105 mg/g), Al: 91% (19 mg/g), Zn: 96% (18 mg/g), Ni: 94% (18 mg/g)	Ilyas and Lee, 2014
<i>At. ferrooxidans</i> , <i>Leptospirillum ferrooxidans</i> , <i>At. thiooxidans</i>	Temperature: 25 °C; pH: 1.7	Cu: 95% (106 mg/g)	Bas et al., 2013
<i>Acidithiobacillus ferrooxidans</i> , <i>Acidithiobacillus thiooxidans</i> , <i>Leptospirillum ferrooxidans</i>	Temperature: 30 °C; n/a; 10% (CRT fluorescent Powder)	Y: 70%	Beolchini et al., 2012
<i>Acidophilic consortium</i> (genera <i>Acidithiobacillus</i> and <i>Gallionella</i>)	Temperature: 30 °C; pH: 2.0	Cu: 97% (626 mg/g), Al: 88% (34 mg/g), Zn: 92% (28 mg/g)	Zhu et al., 2011
<i>At. ferrooxidans</i> , <i>At. thiooxidans</i>	Temperature: 28 °C; pH: 1.5–3.5	Cu: 94%; Ni: 89%; Zn: 90%;	Liang et al., 2010
<i>Chromobacterium violaceum</i> , <i>Pseudomonas fluorescens</i> , <i>Pseudomonas plecoglossicida</i>	Temperature: 30 °C; pH: 7.2–9.2;	Au: 69%	Brandl et al., 2008
<i>Sulfobacillus thermosulfidooxidans</i> , <i>acidophilic isolate</i>	Temperature: 45 °C; pH: 2.0;	Cu: 89% (76 mg/g), Ni: 81% (16.2 mg/g), Zn: 83% (66.4 mg/g)	Ilyas et al., 2007
<i>Aspergillus niger</i> , <i>Penicillium simplicissimum</i>	Temperature: 30 °C; pH: 3.5	Cu 65% (52 mg/g), Al 95% (225 mg/g), Ni 95% (14 mg/g), Zn 95% (25 mg/g)	Brandl et al., 2001
<i>Acidithiobacillus ferrooxidans</i>	Initial pH 3, Initial Fe ³⁺ 8.4 g/L, pulp density 20 g/L, particle size 95 µm.	Cu: 100%; Ni 100%	Arshadi and Mousavi, 2014
<i>Acidithiobacillus ferrooxidans</i>	Initial pH of 1, initial Fe ³⁺ concentration of 4.18 g/L, pulp density of 8.5 g/L and particle size of 114.02 µm (#100 mesh)	Cu: 100%; Ni: 100%	Arshadi and Mousavi, 2015
<i>Bacillus megaterium</i>	Mobile phone PCBs; Initial pH: 10, pulp density: 8.13 g/L, Glycine: 10 g/L.	Cu: 72%; Au: (65 g Au/ton).	Arshadi et al., 2016
<i>Aspergillus niger</i>	Spore suspension: 1 mL (approximately 10 ⁷ spores/mL) Pulp density: 1% (w/v); Shaking speed: 130 rpm; Temperature: 30 °C; Incubation period: 30 days	Li: 100%; Cu 94%; Mn: 72%, Al 62%; Ni: 45%; Co: 38%	Horeh et al., 2018
<i>Acidithiobacillus ferrooxidans</i>	Initial pH: 1, Particle size 62 µm, initial Fe ³⁺ : 9.7 g/L	Ni 87%, Cd 67%, Co 93.7%	Bajestani et al., 2014
<i>Aspergillus niger</i>	Room temperature, Rotation speed 120 rpm; Pulp densities (0.5 g/L to 20 g/L); Incubation: 30 days	Zn: 100%; Ni: 80.39%; Cu: 85.88%	Faraji et al., 2018
<i>Acidithiobacillus ferrooxidans</i>	pH 2.25, Initial Fe(II) 9 g/L, Metal concentrates: 12 g/L, Inoculation quantity 10%; Particle size 0.178–0.250 mm, Incubated 78 h, and for Zn (183 h)	Cu: 92.57%; Al: 85.24%; Zn: 95.18%	Yang et al., 2017a
<i>Acidithiobacillus ferrooxidans</i>	Waste PCBs concentration 15 g/L, 72 h	Cu: 96.8%; Zn: 83.8%; Al: 75.4%	Yang et al., 2014

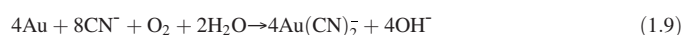
cultivate bacterial culture as well as to maintain the solubilisation process, and also need to add the sulphur or Fe(II) in growth medium (Lambert et al., 2015; Latorre et al., 2016). Current methods are mostly based on a hydrometallurgical approach for gold extraction from e-waste, which may possess secondary pollution. In other words, the hydrometallurgical method is not an environment-friendly solution (Işıldar et al., 2018). The bacterial cyanide secretion has been well known for several years, and gold mobilisation through bacterial *C. violaceum* has been even frequently reported by many researchers (Li, Zeng, et al., 2015). However, very limited research carried out about the removal of gold and/or other metals from e-waste by using indigenous cyanogenic strains (Kumar et al., 2018). In this context, Kumar and co-authors (2018) reported potential indigenous bacterial strain (*Pseudomonas balearica* SAE1). This bacterial strain was isolated from an e-waste recycling site in India. The maximum 68.5% of gold and 33.8% of Ag were dissolved in the two-step bioleaching process, under the optimized condition (pH 9.0, pulp density 10 g/L, the concentration of glycine 5 g/L, at 30 °C).

In other research, Sheel and Pant (2018) developed a modified process by using the mixture of *Lactobacillus acidophilus* (LA) and ammonium thiosulfate (AT) for gold recovery from waste PCBs. This method offers an exceptional leaching system for gold recovery and resulted in 85% of the gold extraction (using AT as leachate) through the suggested mixture. Pant et al. (2014) reported about the indigenous microorganism isolated from the CRT collection/recycling site in India. These studies revealed that the bioassisted process is a promising approach for metal bioleaching from waste CRT, by using the combination of *Serratia plymuthica* and EDTA. The potential use of CRT bioleaching possibly depends on the improvement in metal movement through metal hydrous oxide formation; complex shifting mononuclear to multinuclear. It is expected that the microbial combination with EDTA shows the potential ability to improve

the bioleaching rate. Also, this approach is economically feasible and comparatively eco-friendly than chemical leaching, for example, Hydrocyanic acid (HCN) secreted by heterotrophic bacterial strains, such as *Pseudomonas fluorescens* and *Chromobacterium violaceum* and the HCN produced by *Pseudomonas plecoglossicida* well-reported decade ago, by Brandl and Faramarzi (2006). Gold dissolution by (bio-)cyanidation involves of anodic reaction (Eq. 1.7) and a reaction of cathodic (Eq. 1.8):



Generally, the reaction is recognized as Elsner's equation, as presented in Eq. 1.9, by Kita and co-authors (2006).



Faramarzi et al. (2004) said that similar reactions could be used for the cyanidation of other metals. HCN pKa is 9.3; however optimum pH ranges among 7 and 8 in the case of *C. violaceum* plus other cyanogenic bacteria for cyanogenesis. During the cyanogenesis phase, *C. violaceum* quickly consumes dissolved oxygen; so, slight molecular oxygen is accessible for Au dissolution (Eqs. 1.6 to 1.8). From an environmental point, a recovery is better than the gold mining from mines. For example, a systematic illustration of using microorganisms (bacteria or fungi) for recovery of metals from e-waste is as shown in Fig. 1.

Infect the gold dissolution rate is being subject to several factors; such as particle size, pH, cyanide concentration, temperature, dissolved oxygen concentration, and cyanide complexation antagonism for other metals (Zhou et al., 2020). In microbial cyanidation methods, the pH is certainly

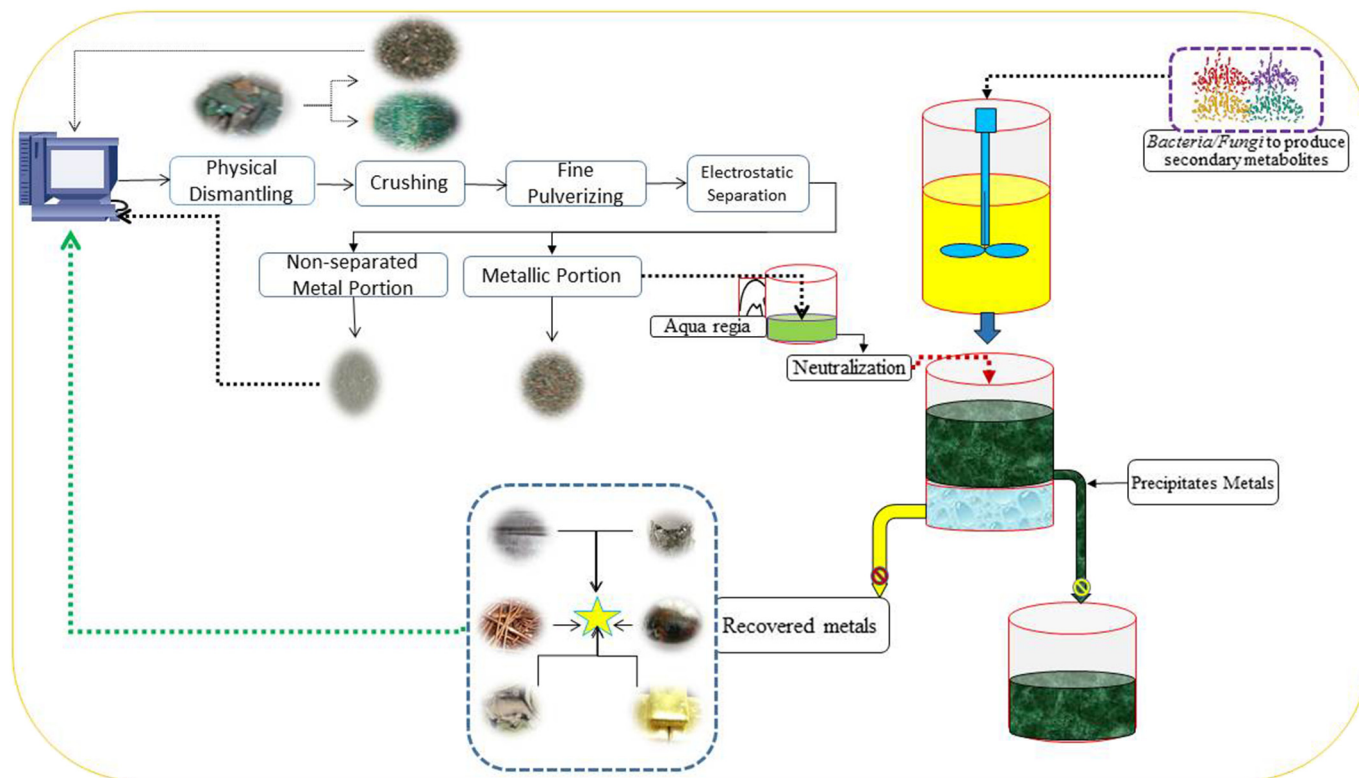


Fig. 1. An example of outline application of microbial metabolites for metal removal from e-waste (e.g., waste PCB) [manually dismantled along with mechanically crushed & dissolved. Next, the microbial culture producing metabolites used as leaching agent]. This process is for the systematic removal of metals from e-waste, for example in precipitated form.

one of the most important factor, because it can significantly affect the growth rate of bacterial culture as well as the presence of cyanide ions. Certainly, an extraction through the cyanidation process needs alkaline conditions, which makes this process unfeasible for the growth of bacterial strains of *C. violaceum* (Kita et al., 2006; Mishra and Rhee, 2014). In general, in order to achieve the appropriate leaching conditions, there are challenging points; such as co-existence of other heavy metals. For example, Cu and other valuable metals present in e-waste can compete with gold in the process of complexation with cyanide anion.

Apart from the bacterial strain, there are other microorganisms; such as fungi can also solubilize the metals. The fungi operate by various mechanisms, where the production of weak organic acids is known to participate as a major operating mechanism in the metal solubilisation process. Certainly, organic acids, such as citric, gluconic and oxalic acids can solubilize metals through establishing complexolysis (Horeh et al., 2018; Xia et al., 2018a, 2018b). Besides, fungi produce carboxylic acids can also attack (acidolysis) on the mineral surface through their protons then release of metals (Gadd, 2007). Metal complexation occurs with organic functional groups (e.g. amine, carboxyl, phosphate, carbonyl, hydroxyl, and other groups) on the cell wall surface (Wang and Chen, 2009), and we can expect that fungus *A. niger* is accomplished bioleaching about 80.39% of Ni, 85.88% of Cu, and 100% of Zn, after 30 days. Another study by Narayanasamy et al. (2018) used the fungal strain (*Aspergillus niger* DDNS1) for extraction of metal from waste PCBs, and their findings revealed that the toxicity of waste PCBs powder (0.1% pulp density) had less effect on two-step bioleaching method than one-step bioleaching method. The number of researchers suggested strategies such as: (1) Pre-adaptation of using different microorganisms (Ilyas et al., 2014; Pourhossein and Mousavi, 2018); (2) Two-step bioleaching approach (Brandl et al., 2001; Naseri et al., 2019); (3) Pre-treatment by removing the non-metallic portion (Ilyas et al., 2007). Research conducted by Shah et al. (2015) established that in a bioleaching action with a two-step approach, PCB powder additions at different periods can increase the overall

feasibility of different metals, such as 99.80% of Zn; 97.99% of Ni, and 94.08% of Cu were removed. Bioleaching approach is not appropriate in case removal of Tin (Sn) and Lead (Pb), owing to bioleaching strategy seems to suffer from the issue of precipitation of Sn and Pb (because Pb would be precipitate as $PbSO_4$ and Sn as SnO) (Yang et al., 2017a, 2017b). Therefore, these studies suggest, the microbial technology approach could symbolize as a useful strategy. In this context, another outstanding initiative already announced by the “2020 Tokyo Olympics”, Japan, where all the medals (gold, silver, and bronze) will be manufactured by using recycled e-waste (<https://phys.org/news/2019-02-tokyo-gold-silver-bronze-e-waste.html>). This is a very positive step towards e-waste recycling and management in an environmentally sound approach.

5. Summary and conclusion

This article discussed some of the well-recognized recycling methods, and these methods reported as high potential candidate for the valuable metal recycling from e-waste, and suitable for the removing secondary resources from e-waste. Although, the metal recycling process remains a challenging issue. However, e-waste can give a high value of metal content making it a suitable secondary resource. In order to safely extract present valuable metals, remove the other toxic and environmentally hazardous materials, the e-waste should be properly treated using environmentally sound methods.

Declaration of competing interest

The authors declare no potential conflict of interest.

Acknowledgements

The authors wish to acknowledge the helpful contributions of anonymous reviewers and the editorial team input from Current Research in

Biotechnology. V.K.G. and M.H. would like to acknowledge funding from the EU 7th Framework Programme for research, technological development and demonstration activities under grant agreement No. 621364 (TUTIC-Green), that provided support to make this work. A.K.A. would like to acknowledge Prof. Jinhui Li, for kind support and suggestions for this article.

References

- Al-Ghouti, M.A., Abuqaoud, R.H., Abu-Dieyeh, M.H., 2016. Detoxification of mercury pollutant leached from spent fluorescent lamps using bacterial strains. *Waste Manag.* 49, 238–244.
- Arshadi, M., Mousavi, S.M., 2014. Simultaneous recovery of Ni and Cu from computer-printed circuit boards using bioleaching: statistical evaluation and optimization. *Bioresour. Technol.* 174, 233–242.
- Arshadi, M., Mousavi, S.M., 2015. Multi-objective optimization of heavy metals bioleaching from discarded mobile phone PCBs: simultaneous Cu and Ni recovery using *Acidithiobacillus ferrooxidans*. *Sep. Purif. Technol.* 147, 210–219.
- Arshadi, M., Mousavi, S.M., Rasoulinia, P., 2016. Enhancement of simultaneous gold and copper recovery from discarded mobile phone PCBs using *Bacillus megaterium*: RSM based optimization of effective factors and evaluation of their interactions. *Waste Manag.* 57, 158–167.
- Arshadi, M., Nili, S., Yaghmaei, S., 2019. Ni and Cu recovery by bioleaching from the printed circuit boards of mobile phones in non-conventional medium. *J. Environ. Manag.* 15 (109502), 250.
- Awasthi, A.K., Li, J., 2017a. Management of electrical and electronic waste: a comparative evaluation of China and India. *Renew. Sust. Energ. Rev.* 76, 434–447.
- Awasthi, A.K., Li, J., 2017b. An overview of the potential of eco-friendly hybrid strategy for metal recycling from WEEE. *Resour. Conserv. Recycl.* 126, 228–239.
- Awasthi, A.K., Zeng, X., Li, J., 2016. Environmental pollution of electronic waste recycling in India: a critical review. *Environ. Pollut.* 211, 259–270.
- Awasthi, A.K., Cucchiella, F., D'Adamo, I., Li, J., Rosa, P., Terzi, S., Wei, G., Zeng, X., 2018. Modelling the correlations of e-waste quantity with economic increase. *Sci. Total Environ.* 613–614, 46–53.
- Awasthi, A.K., Li, J., Koh, L., Ogunseitan, O.A., 2019. Circular economy and electronic waste. *Nat. Electron.* 2, 86–89.
- Bajestani, M.I., Mousavi, S.M., Shojaosadati, S.A., 2014. Bioleaching of heavy metals from spent household batteries using *Acidithiobacillus ferrooxidans*: statistical evaluation and optimization. *Sep. Purif. Technol.* 132, 309–316.
- Baldé, C.P., Forti, V., Gray, V., Kuehr, R., Stegmann, P., 2017. The Global E-Waste Monitor. United Nations University (UNU), International Telecommunication Union (ITU) & International Solid Waste Association (ISWA), Bonn/Geneva/Vienna http://collections.unu.edu/eserv/UNU:6341/Global-E-waste-Monitor-2017_electronic_single_pages.pdf.
- Banerjee, I., Burrell, B., Reed, C., West, A.C., Banta, S., 2017. Metals and minerals as a biotechnology feedstock: engineering biomining microbiology for bioenergy applications. *Curr. Opin. Biotechnol.* 45, 144–155.
- Baniasadi, M., Vakilchah, F., Bahaloo-Horeh, N., Mousavi, S.M., Farnaud, S., 2019. Advances in bioleaching as a sustainable method for metal recovery from e-waste: a review. *J. Ind. Eng. Chem.* 76, 75–90.
- Bas, A.D., Deveci, H., Yazici, E.Y., 2013. Bioleaching of copper from low grade scrap TV circuit boards using mesophilic bacteria. *Hydrometallurgy* 138, 65–70.
- Beolchini, F., Fonti, V., Dell'Anno, A., Rocchetti, L., Vegliò, F., 2012. Assessment of biotechnological strategies for the valorization of metal bearing wastes. *Waste Manag.* 32, 949–956.
- Bindschedler, S., Bouquet, T.Q.T.V., Job, D., Joseph, E., Junier, P., 2017. Fungal biorecovery of gold from E-waste. *Adv. Appl. Microbiol.* 99, 53–81. <https://doi.org/10.1016/bs.aams.2017.02.002>.
- Brandl, H., Faramarzi, M.A., 2006. Applying microbe–metal–interactions for the biotechnological treatment of mineral waste. *China Particul.* 4, 93–97.
- Brandl, H., Bosshard, R., Wegmann, M., 2001. Computer-munching microbes: metal leaching from electronic scrap by bacteria and fungi. *Hydrometallurgy* 59, 319–326.
- Brandl, H., Lehmann, S., Faramarzi, M.A., Martinelli, D., 2008. Biomobilization of silver, gold, and platinum from solid waste materials by HCN-forming microorganisms. *Hydrometallurgy* 94, 14–17.
- Brown, T.J., Shaw, R.A., Bide, T., Petavratzi, E., Raycraft, E.R., Walters, A.S., 2013. World Mineral Production 2007–11. British Geological Survey.
- Chen, S., Yang, Y., Liu, C., Dong, F., Liu, B., 2015. Column bioleaching copper and its kinetics of waste printed circuit boards (WPCBs) by *Acidithiobacillus ferrooxidans*. *Chemosphere* 141, 162–168.
- Chi, T.D., Jae-chun, Lee, Pandey, B.D., Yoo, K., Jeong, J., 2011. Bioleaching of gold and copper from waste mobile phone PCBs by using a cyanogenic bacterium. *Miner. Eng.* 24, 1219–1222.
- Cucchiella, F., D'Adamo, I., Koh, S.C.L., Rosa, P., 2015. Recycling of WEEEs: an economic assessment of present and future e-waste streams. *Renew. Sust. Energ. Rev.* 51, 263–272.
- Diniz, V., Volesky, B., 2005. Biosorption of La, Eu and Yb using *Sargassum* biomass. *Water Res.* 39, 239–247.
- Duan, H., Hu, J., Tan, Q., Liu, L., Wang, Y., Li, J., 2016. Systematic characterization of generation and management of e-waste in China. *Environ. Sci. Pollut. Res.* 23, 1929–1943.
- Faraji, F., Golmohammadzadeh, R., Rashchi, F., Alimardani, N., 2018. Fungal bioleaching of WPCBs using *Aspergillus niger*: observation, optimization and kinetics. *J. Environ. Manag.* 217, 775–787.
- Faramarzi, M.A., Stagars, M., Pensini, E., Krebs, W., Brandl, H., 2004. Metal solubilization from metal-containing solid materials by cyanogenic *Chromobacterium violaceum*. *J. Biotechnol.* 113, 321–326.
- Fathollahzadeh, H., Becker, T., Eksteen, J.J., Kaksonen, A.H., Watkin, E.L.J., 2018. Microbial contact enhances bioleaching of rare earth elements. *Bioresour. Technol. Rep.* 3, 102–108.
- Fomina, M., Gadd, G.M., 2014. Biosorption: current perspectives on concept, definition and application. *Bioresour. Technol.* 160, 3–14.
- Gadd, G.M., 2007. Geomycology: Biogeochemical transformations of rocks, minerals, metals and radionuclides by fungi, bioweathering and bioremediation. *Mycological Res.* 111, 3–49.
- Gadd, G.M., 2009. Biosorption: critical review of scientific rationale, environmental importance and significance for pollution treatment. *J. Chem. Technol. Biotechnol.* 84 (1), 13–28.
- Hassan, S.H.A., Koutb, M., Nafady, N.A., Hassan, E.A., 2018. Potentiality of *Neopetalotopsis clavispora* ASU1 in biosorption of cadmium and zinc. *Chemosphere* 202, 750–756.
- Henckens, M.L.C.M., Driessen, P.P.J., Worrell, E., 2014. Metal scarcity and sustainability, analyzing the necessity to reduce the extraction of scarce metals. *Resour. Conserv. Recycl.* 93, 1–8.
- Hennebel, T., Boon, N., Maes, S., Lenz, M., 2017. Biotechnologies for critical raw material recovery from primary and secondary sources: R&D priorities and future perspectives. *Nat. Biotechnol.* 32 (1), 121–127.
- Heydarian, A., Mousavi, S.M., Vakilchah, F., Baniasadi, M., 2018. Application of a mixed culture of adapted acidophilic bacteria in two-step bioleaching of spent lithium-ion laptop batteries. *J. Power Sources* 378, 19–30.
- Hong, Y., Valix, M., 2014. Bioleaching of electronic waste using acidophilic sulfur oxidizing bacteria. *J. Clean. Prod.* 65, 465–472.
- Hopfe, S., Flemming, K., Lehmann, F., Möckel, R., Kutschke, S., Pollmann, K., 2017. Leaching of rare earth elements from fluorescent powder using the tea fungus *Kombucha*. *Waste Manag.* 62, 211–221.
- Horeh, N., Mousavi, S.M., Baniasadi, M., 2018. Use of adapted metal tolerant *Aspergillus niger* to enhance bioleaching efficiency of valuable metals from spent lithium-ion mobile phone batteries. *J. Clean. Prod.* 197, 1546–1557.
- Huisman, J., Botezatu, I., Herreras, L., Liddane, M., Hints, J., Luda di Cortemiglia, V., Leroy, P., Vermeersch, E., Mohanty, S., van den Brink, S., Ghenciu, B., Dimitrova, D., Nash, E., Shryane, T., Wieting, M., Kehoe, J., Baldé, C.P., Magalini, F., Zanasi, A., Ruini, F., Männistö, T., Bonzio, A., 2015. Countering WEEE Illegal Trade (CWIT) Summary Report, Market Assessment, Legal Analysis, Crime Analysis and Recommendations Roadmap, August 30, 2015, Lyon, France. <http://www.cwitproject.eu/wp-content/uploads/2015/09/CWIT-Final-Report.pdf>.
- Hunt, A.J., Farmer, T.J., Clark, J.H., 2013. Chapter 1: Elemental sustainability and the importance of scarce element recovery. In: Hunt, Andrew J. (Ed.), *Element Recovery and Sustainability*. Royal Society of Chemistry, pp. 1–28.
- Ilyas, S., Lee, J.C., 2014. Bioleaching of metals from electronic scrap in a stirred tank reactor. *Hydrometallurgy* 149, 50–62.
- Ilyas, S., Anwar, M.A., Niazi, S.B., Afzal Ghauri, M., 2007. Bioleaching of metals from electronic scrap by moderately thermophilic acidophilic bacteria. *Hydrometallurgy* 88, 180–188.
- Ilyas, S., Lee, J., Kim, B., 2014. Biorecovery of heavy metals from recycling industry electronic waste by a consortium of moderate thermophiles: process development and optimization. *J. Clean. Prod.* 70, 194–202.
- İşildar, A., van de Vossenberg, J., Rene, E.R., van Hullebusch, E.D., Lens, N.L., 2016. Two-step bioleaching of copper and gold from discarded printed circuit boards (PCB). *Waste Manag.* 57, 149–157.
- İşildar, A., Rene, E.R., van Hullebusch, E.D., Lens, P.N.L., 2018. Electronic waste as a secondary source of critical metals: management and recovery technologies. *Resour. Conserv. Recycl.* 135, 296–312.
- Jiang, B., Adebayo, A., Jiad, J., Xing, Y., Deng, S., Guo, L., Liang, Y., Zhang, D., 2019. Impacts of heavy metals and soil properties at a Nigerian e-waste site on soil microbial community. *J. Hazard. Mater.* 362, 187–195.
- Johnson, D.B., 2014. Biomining—biotechnologies for extracting and recovering metals from ores and waste materials. *Curr. Opin. Biotechnol.* 30, 24–31.
- Jowkar, M.J., Horeh, N.B., Mousavi, S.M., Pourhossein, F., 2018. Bioleaching of indium from discarded liquid crystal displays. *J. Clean. Prod.* 180, 417–429.
- Jujun, R., Xingjiong, Z., Yiming, Q., Jian, H., 2014. A new strain for recovering precious metals from waste printed circuit boards. *Waste Manag.* 34, 901–907.
- Kaksonen, A.H., Boxall, N.J., Gumulya, Y., Khaleque, H.N., Morris, C., Bohu, T., Cheng, K.Y., Usher, K., Lakanemi, A.M., 2018. Recent progress in biohydrometallurgy and microbial characterisation. *Hydrometallurgy* 180, 7–25.
- Kaya, M., 2016. Recovery of metals and nonmetals from electronic waste by physical and chemical recycling processes. *Waste Manag.* 57, 64–90.
- Khoo, K.M., Ting, Y.P., 2001. Biosorption of gold by immobilized fungal biomass. *Biochem. Eng. J.* 8 (1), 51–59.
- Kita, Y., Nishikawa, H., Takemoto, T., 2006. Effects of cyanide and dissolved oxygen concentration on biological Au recovery. *J. Biotechnol.* 124, 545–551.
- Kumar, A., Saini, H.S., Kumar, S., 2018. Bioleaching of gold and silver from waste printed circuit boards by *Pseudomonas balearica* SAE1 isolated from an e-waste recycling facility. *Curr. Microbiol.* 75, 194–201.
- Lambert, F., Gaydardzhiev, S., Léonard, G., Lewis, G., Bareel, P.F., Bastin, D., 2015. Copper leaching from waste electric cables by bio-hydrometallurgy. *Miner. Eng.* 76, 38–46.
- Latorre, M., Cortés, M.P., Travisany, D., Genova, A., Di, Budinich M., Reyes-Jara, A., Hödar, C., González, M., Parada, P., Bobadilla-Fazzini, R.A., Cambiazo, V., Maass, A., 2016. The bioleaching potential of a bacterial consortium. *Bioresour. Technol.* 218, 659–666.
- Lewis, G., Gaydardzhiev, S., Bastin, D., Bareel, P.F., 2011. Bio-hydrometallurgical recovery of metals from fine shredder residues. *Miner. Eng.* 24, 1166–1171.
- Li, J., Zeng, X., Chen, M., Ogunseitan, O.A., Stevels, A.L.N., 2015a. “Control-Alt-Delete”: rebooting solutions for the e-waste problem. *Environ. Sci. Technol.* 49 (12), 7095–7108.
- Li, J., Liang, C., Ma, C., 2015b. Bioleaching of gold from waste printed circuit boards by *Chromobacterium violaceum*. *J. Mater. Cycles Waste Manag.* 17, 529–539.
- Liang, G., Mo, Y., Zhou, Q., 2010. Novel strategies of bioleaching metals from printed circuit boards (PCBs) in mixed cultivation of two acidophiles. *Enzym. Microb. Technol.* 47, 322–326.
- Ma, H.W., Liao, X.P., Liu, X., Shi, B., 2006. Recovery of platinum (IV) and palladium(II) by bayberry tannin immobilized collagen fibre membrane from water solution. *J. Membr. Sci.* 278, 373–380.

- Maneesuwannarat, S., Vangnai, A.S., Yamashita, M., Thiravetyan, P., 2016. Bioleaching of gallium from gallium arsenide by *Cellulosimicrobium funkei* and its application to semiconductor/electronic wastes. *Process. Saf. Environ. Prot.* 99, 80–87.
- Marra, A., Cesaro, A., Rene, E.R., Belgiojorno, V., Lens, P.N.L., 2018. Bioleaching of metals from WEEE shredding dust. *J. Environ. Manag.* 210, 180–190.
- Marsh, A.J., O'Sullivan, O., Hill, C., Ross, R.P., Cotter, P.D., 2014. Sequence-based analysis of the bacterial and fungal compositions of multiple Kombucha (tea fungus) samples. *Food Microbiol.* 38, 171–178.
- Meskers, C., 2009. Umicore Precious Metals Refining, Guest Lecture Presentation for e-Waste Recycling at Delft University of Technology, 8 September 2009, Delft, the Netherlands.
- Meylan, G., Reck, B.K., 2017. The anthropogenic cycle of zinc: status quo and perspectives. *Resour. Conserv. Recycl.* 123 (1–10).
- Mishra, D., Rhee, Y.H., 2014. Microbial leaching of metals from solid industrial wastes. *J. Microbiol.* 52, 1–7.
- More, T.T., Yadav, J.S.S., Yan, S., Tyagi, R.D., Surampalli, R.Y., 2014. Extracellular polymeric substances of bacteria and their potential environmental applications. *J. Environ. Manag.* 144, 1–25.
- Nakamura, T., Halada, K., 2015. *Urban Mining Systems. Briefs in Applied Sciences and Technology*. Springer, pp. 1–50. https://doi.org/10.1007/978-4-431-55075-4_2.
- Nancharaiyah, Y.V., Mohan, S.V., Lens, P.N.L., 2015. Metals removal and recovery in bioelectrochemical systems: a review. *Bioresour. Technol.* 195, 102–114.
- Nancharaiyah, Y.V., Mohan, S.V., Lens, P.N.L., 2016. Biological and bioelectrochemical recovery of critical and scarce metals. *Trends Biotechnol.* 34 (2), 137–155.
- Narayananamy, M., Dhanasekaran, D., Vinothini, G., Thajuddin, N., 2018. Extraction and recovery of precious metals from electronic waste printed circuit boards by bioleaching acidophilic fungi. *Int. J. Environ. Sci. Technol.* 15, 119–132.
- Naseem Akthar, M., Sivarama Sastry, K., Maruthi, M.P., 1995. Biosorption of silver ions by processed *Aspergillus niger* biomass. *Biotechnol. Lett.* 17 (5), 551–556.
- Naseri, T., Bahaloo-Horeh, N., Mousavi, S.M., 2019. Environmentally friendly recovery of valuable metals from spent coin cells through two-step bioleaching using *Acidithiobacillus thiooxidans*. *J. Environ. Manag.* 235, 357–367.
- Niu, Z., Huang, Q., Wang, J., Yang, Y., Xin, B., Chen, S., 2015. Metallic ions catalysis for improving bioleaching yield of Zn and Mn from spent Zn-Mn batteries at high pulp density of 10%. *J. Hazard. Mater.* 298, 170–177.
- Odeyingbo, O., Nnorom I. and Deubzer, O., 2017. Person in the Port Project: Assessing Import of Used Electrical and Electronic Equipment into Nigeria. UNU-ViE SCYCLE and BCCC Africa.
- Pant, D., Singh, P., 2013. Chemical modification of waste glass from cathode ray tubes (CRTs) as low cost adsorbent. *J. Environ. Chem. Eng.* 1, 226–232.
- Pant, D., Singh, P., Upreti, M.K., 2014. Metal leaching from cathode ray tube waste using combination of *Serratia plymuthica* and EDTA. *Hydrometallurgy* 146, 89–95.
- Podar, M., Reysenbach, A.L., 2006. New opportunities revealed by biotechnological explorations of extremophiles. *Curr. Opin. Biotechnol.* 17, 250–255.
- Pollmann, K., Kutschke, S., Matys, S., Raff, J., Hlawacek, G., Lederer, F.L., 2018. Bio-recycling of metals: recycling of technical products using biological applications. *Biotechnol. Adv.* 36, 1048–1062.
- Pourhossein, F., Mousavi, S.M., 2018. Enhancement of copper, nickel, and gallium recovery from LED waste by adaptation of *Acidithiobacillus ferrooxidans*. *Waste Manag.* 79, 98–108.
- Rozas, E.E., Mendes, M.A., Custódio, M.R., Espinosa, D.C.R., Nascimento, C.A.O.do., 2019. Self-assembly of supramolecular structure based on copper-lipopeptides isolated from e-waste bioleaching liquor. *J. Hazard. Mater.* 368, 63–71.
- Sahni, A., Kumar, A., Kumar, S., 2016. Chemo-biohydrometallurgy—a hybrid technology to recover metals from obsolete mobile SIM cards. *Environ. Nanotechnol. Monit. Manag.* 6, 130–133.
- Salazar, K., 2013. *Mineral Commodity Summaries 2013: US Geological Survey (USGS)*. US Geological Survey.
- Senophiyah-Mary, J., Loganath, R., Shameer, P.M., 2018. Deterioration of cross linked polymers of thermoset plastics of e-waste as a side part of bioleaching process. *J. Environ. Chem. Eng.* 6, 3185–3191.
- Shah, M.B., Tipre, D.R., Purohit, M.S., Dave, S.R., 2015. Development of two-step process for enhanced biorecovery of Cu-Zn-Ni from computer printed circuit boards. *J. Biosci. Bioeng.* 120 (2), 167–173.
- Sheel, A., Pant, D., 2018. Recovery of gold from electronic waste using chemical assisted microbial biosorption (hybrid) technique. *Bioresour. Technol.* 247, 1189–1192.
- Song, Li, 2014. Environmental effects of heavy metals derived from the e-waste recycling activities in China: a systematic review. *Waste Manag.* 34 (12), 2587–2594.
- Song, Q., Zhang, L., Xu, Z., 2020. Indium recovery from In-Sn-Cu-Al mixed system of waste liquid crystal display panels via acid leaching and two-step electrodeposition. *J. Hazard. Mater.* 381, 120973.
- Shthianopkao, S., Wong, M.H., 2013. Handling e-waste in developed and developing countries: initiatives, practices, and consequences. *Sci. Total Environ.* 463–464, 1147–1153.
- Sun, M., Wang, Y., Hong, J., Dai, J., Wang, R., Niu, Z., Xin, B., 2016. Life cycle assessment of a biohydrometallurgical treatment of spent Zn-Mn batteries. *J. Clean. Prod.* 129, 350–358.
- Swain, B., Lee, C.G., 2019. Commercial indium recovery processes development from various e-(industry) waste through the insightful integration of valorization processes: a perspective. *Waste Manag.* 87, 597–611.
- Tansel, B., 2017. From electronic consumer products to e-wastes: global outlook, waste quantities, recycling challenges. *Environ. Int.* 98, 35–45.
- Ting, Y.P., Mittal, A.K., 2002. Effect of pH on the biosorption of gold by a fungal biosorbent. *Resour. Environ. Biotechnol.* 3 (4), 229–239.
- Vats, M.C., Singh, S.K., 2015. Assessment of gold and silver in assorted mobile phone printed circuit boards (PCBs). *Waste Manag.* 45, 280–288.
- Vendruscolo, F., Ferreira, G. L.da R., Filho, N.R.A., 2017. Biosorption of hexavalent chromium by microorganisms. *Int. Biodeterior. Biodegrad.* 119, 87–95.
- Wang, J., Chen, C., 2009. Biosorbents for heavy metals removal and their future. *Biotechnol. Adv.* 27, 195–226.
- Wang, J., Bai, J., Xu, J., Liang, B., 2009. Bioleaching of metals from printed wire boards by *Acidithiobacillus ferrooxidans* and *Acidithiobacillus thiooxidans* and their mixture. *J. Hazard. Mater.* 172, 1100–1105.
- Wang, F., Huisman, J., Meskers, C.E.M., Schluep, M., Ab, Stevels, Hagelüken, C., 2012. The Best-of-2-Worlds philosophy: developing local dismantling and global infrastructure network for sustainable e-waste treatment in emerging economies. *Waste Manag.* 32, 2134–2146.
- Widmer, R., Oswald-Krapf, H., Khetriwal, D.S., Schnellmann, M., Böni, H., 2005. Global perspectives on e-waste. *Environ. Impact Assess. Rev.* 25 (5), 436–458.
- Won, S.W., Kotte, P., Wei, W., Lim, A., Yun, Y.S., 2014. Biosorbents for recovery of precious metals. *Bioresour. Technol.* 160, 203–212.
- Wong, M.H., Wu, S.C., Deng, W.J., Yu, X.Z., Luo, Q., Leung, A.O.W., 2007. Export of toxic chemicals—a review of the case of uncontrolled electronic-waste recycling. *Environ. Pollut.* 149 (2), 131–140.
- Wu, W., Liu, X., Zhang, X., Zhu, M., Tan, W., 2018. Bioleaching of copper from waste printed circuit boards by bacteria-free cultural supernatant of iron-sulfur oxidizing bacteria. *Bioresour. Bioprocess.* 5 (10), 1–13. <https://doi.org/10.1186/s40643-018-0196-6>.
- Xia, M., Bao, P., Liu, A., Wang, M., Shen, L., Yu, R., Liu, Y., Chen, M., Li, J., Wu, X., Qiu, G., Zeng, W., 2018a. Bioleaching of low-grade waste printed circuit boards by mixed fungal culture and its community structure analysis. *Resour. Conserv. Recycl.* 136, 267–275.
- Xia, M.C., Bao, P., Liu, A.J., Zhang, S.S., Peng, T.J., Shen, L., Yu, R.L., Wu, X.L., Li, J.K., Liu, Y.D., Chen, Miao, Qiu, G.Z., Zeng, W.M., 2018b. Isolation and identification of *Penicillium chrysogenum* strain Y5 and its copper extraction characterization from waste printed circuit boards. *J. Biosci. Bioeng.* 126 (1), 78–87.
- Xiang, Y., Wu, P., Zhu, N., Zhang, T., Liu, W., Wu, J., Li, P., 2010. Bioleaching of copper from waste printed circuit boards by bacterial consortium enriched from acid mine drainage. *J. Hazard. Mater.* 184 (1–3), 812–818.
- Xin, B., Jiang, W., Aslam, H., Zhang, K., Liu, C., Wang, R., Wang, Y., 2012. Bioleaching of zinc and manganese from spent Zn-Mn batteries and mechanism exploration. *Bioresour. Technol.* 106, 147–153.
- Yang, Y., Chen, S., Li, S., Chen, M., Chen, H., Liu, B., 2014. Bioleaching waste printed circuit boards by *Acidithiobacillus ferrooxidans* and its kinetics aspect. *J. Biotechnol.* 173, 24–30.
- Yang, C., Zhu, N., Shen, W., Zhang, T., Wu, P., 2017a. Bioleaching of copper from metal concentrates of waste printed circuit boards by a newly isolated *Acidithiobacillus ferrooxidans* strain Z1. *J. Mater. Cycles Waste Manag.* 19, 247–255.
- Yang, C., Li, J., Tan, Q., Liu, L., Dong, Q., 2017b. Green process of metal recycling: co-processing waste printed circuit boards and spent tin stripping solution. *ACS Sustain. Chem. Eng.* 5, 3524–3534.
- Yang, C., Tan, Q., Zeng, X., Zhang, Y., Wang, Z., Li, J., 2018. Measuring the sustainability of tin in China. *Sci. Total Environ.* 635, 1351–1359.
- Zeng, X., Li, J., 2015. On the sustainability of cobalt utilization in China. *Resour. Conserv. Recycl.* 104, 12–18.
- Zeng, X., Mathews, J.A., Li, J., 2018. Urban mining of e-waste is becoming more cost-effective than virgin mining. *Environ. Sci. Technol.* 52, 4835–4841.
- Zhou, G., Zhang, H., Yang, W., Wu, Z., Liu, W., Yang, C., 2020. Bioleaching assisted foam fractionation for recovery of gold from the printed circuit boards of discarded cellphone. *Waste Manag.* 101, 200–209.
- Zhuang, W.Q., Fitts, J.P., Ajo-Franklin, C.M., Maes, S., Alvarez-Cohen, L., Hennebe, T., 2015. Recovery of critical metals using biometallurgy. *Curr. Opin. Biotechnol.* 33, 327–335.