Physicochem. Probl. Miner. Process., 59(5), 2023, 167375

http://www.journalssystem.com/ppmp

Physicochemical Problems of Mineral Processing

ISSN 1643-1049

Recent sustainable trends for e-waste bioleaching

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Abstract: For the past few decades, the electronic and electrical waste have been accumulating and piling on our lands and aside from posing some serious threat on our environment and our health. And with the technological advance and the rapid growing electronic demand and production there is the risk of accumulating even more unused valuable usable materials in our waste land-fields. Up to 2030, EU is forecasting about 74 million tons of e-waste, including washing machines, tablet computers, toasters, and cell phones. In 2022, more than 5.3 billion mobile phones were wasted whereas Li, Mn, Cu, Ni, and various rare-earth elements (like Nd, Eu and Tb, etc.) as well as graphite are actually found in the contents of many metal parts from wiring, batteries to their components. The main purpose aside from an environmental aspect is reserving the mineral used in this waste, as many of the crucial materials have a supply risk heavily depending on import. For instance, many of these rare earth elements (REE) are sourced from China; these REEs are used in many electronics that range from consumer products to industrial-use machines. This study is to review one of the desired methods that is via using bio-techniques to dissolve and recover as much as possible from main e-waste sources such as PCBs, spend batteries and LCD/LED panels. Microorganisms that are used for bioleaching process and their metal recovery aspects were compared in the second part. Future perspectives were finally added considering significant techno-economic environmental and social impacts.

Keywords: bioleaching, e-waste, sustainable mining, used electronic components, waste printed circuit boards, recovery metals

1. Introduction

Even though it's called "waste," electronic waste has a great value. Many electronic components are made with palladium, gold, silver, and/or copper that are valuable precious and base metals. In terms of economic value, gold takes first place, comprising about 50% of the possible revenue from reselling materials. Other metals are also worth the recovery efforts, based on their value and the significant volume of these metals present in electronic waste. E-waste disposal are generally based on three main sources: PCBs, spend batteries and LCD/LED panels and secondary recovery uses mineral beneficiation methods based on chemical and metallurgical processes as seen in Fig. 1. Among the others, most metals with economic and reusable value are located in printed circuit boards (PCBs) (EC, 2017). Almost 40% of PCB waste is metals, while about 30% comprises plastics and the remaining 30% is made up of glass and oxides (Sum, 1991). In a common PCB of an ordinary personal computer, 20% of copper and 250 g/ton gold are notable as secondary sources, as these amounts correspond to at least 20-40 and 25-250-fold for copper and gold, respectively (Yazıcı and Deveci, 2013). However, because of the complexity of PCBs and the combination of these materials in its construction, often the most difficult part of the device is to recycle. There are very few companies including (Sims Recycling Solutions - United States, Umicore – Belgium, Boliden Group – Sweden, Stena Technoworld – Sweden, Electronic Recyclers International (ERI) - United States, Veolia – France, EnviroLeach Technologies – Canada, Dowa Holdings – Japan, E-Parisaraa Pvt. Ltd. – India. TES (Technology, Engineering, and Sustainability) – Singapore) that actually recycle PCBs in an effort to retrieve those base metals. And even when PCB recycling process is successful, REEs are often left untapped and unrecovered, thanks to the extremely low concentrations of these materials. For this reason, companies such as Umicore tend to

DOI: 10.37190/ppmp/167375

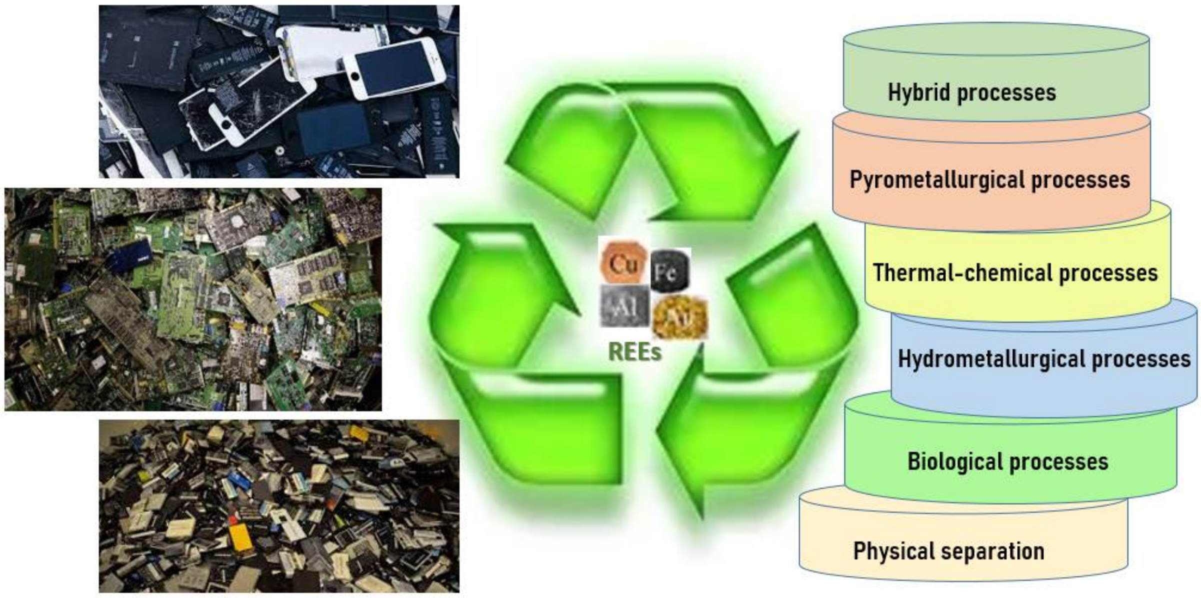

Fig. 1. E-waste recycling and related processing

focus on the economical processing of only high-grade PCBs.

The PCB is responsible for controlling all the device's accessories (such as the screen, motor, and/or battery) via the microcontroller or integrated circuit. A series of various electronic components (ECs) work alongside the microcontroller to adapt electric signals in order to supply power and communicate with the parts. Every EC is constructed according to specific characteristics of each metal it comprises. For example, high temperature resistive paste in most resistors include ruthenium dioxide. Tantalum is used for enhanced dielectric properties in the capacitors (Gill, 2012). So, the PCB comprises the board itself, along with several ECs and other subassemblies; together, they make up the entire product. Throughout this product, certain base and precious metals are located within each component. Thus, the PCB is a highly complex and deeply connected piece of hardware, which leads to the problems faced with recycling (Kaya, 2019). During the PCB recycling process, this complexity reduces access to the reusable and salvageable elements.

2. The process of bio-dismantling

In order to achieve a more complete recycling of all these elements, the board and each of its components must be separated; this requires an inordinate amount of energy and time. Industries are constantly searching for more cost-effective processes; as a result, this first process is the most popular. Often, PCBs are ground down into a powder of homogenous concentrations after physical separation (Fig. 2). This powder offers comparable data, since each sample can be easily defined and characterized. The main drawback of this approach, however, is the higher heterogeneity among various batches, as well as the low grade of the metals from the outset of the process (when they aren't yet dismantled and separated). Another disposal challenge is non-metals parts in the PCBs are in about 70% present consisting of thermoset resins, which cannot be remelted and reinforcing materials, which are mostly inorganic fillers, such as glass fibres (Guo et al., 2008). When different elements and components are characterized separately, critical elements can be found in higher concentrations. As we will discuss later on, this increased efficacy could lead the entire industry to rethink the idea that the recovery of some of these elements is impossible.

In most cases, dismantling is necessary in order to circumvent pollution or to get rid of toxic compounds that exist in the board (e.g., nonsolid electrolyte capacitors). Manually using with a pneumatic tool, or by melting the binding component (solder) is possible to separate the circuit; the latter method is currently being used by the Apple Company. This melting technique produces toxic fumes and also takes a lot of energy to complete; despite that, it is still the preferred pyrometallurgical technique in the industry. No matter the situation, though, ECs much be separated by melting the solder which binds the elements together.

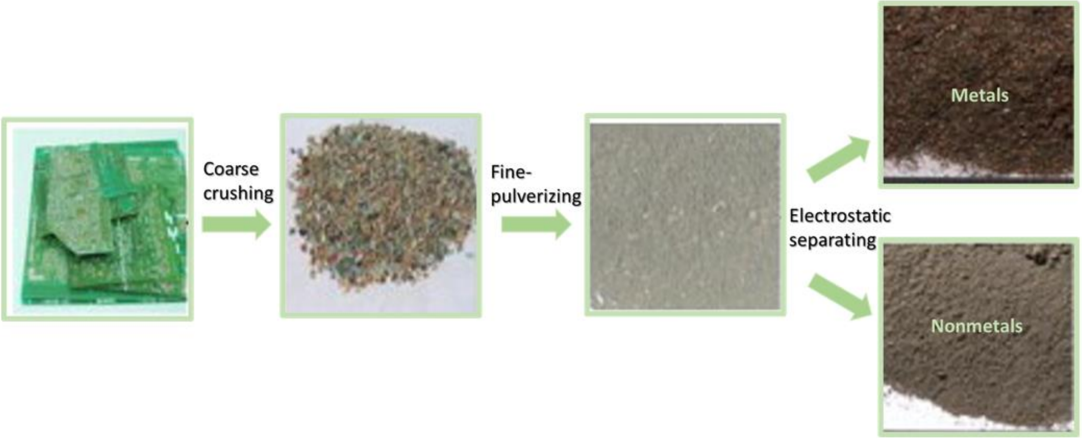

Fig. 2. Crushing and electrostatic separation of PCBs (redrawn from Guo et al., 2008)

Solders are comprised of alloys that conduct electricity between the elements of the PCB. They have a low melting point which complies with each component's specific maximum temperature. Historically, Sn-37Pb, a tin-lead alloy, has been used in such cases; since the melting point under eutectic conditions is 183 °C made it the perfect material for the job. Nowadays, solder technology avoids lead-based solders because of the environmental issues that the heavy metal poses (Lee, 2000).

In terms of lead-free solders, SnAgCu (also known as SAC) is most popular nowadays. The most known SAC alloys are SAC305 which is a lead-free alloy that contains 96.5% tin, 3% silver, and 0.5% copper, and SAC405 (95.5% tin, 4% silver, and 0.5% copper). These compositions make the soldering especially susceptible to the effects of bioleaching, as the process can target the breakdown of specific soldering conditions. This means that bioleaching offers more cost-effective e-waste recycling when compared to conventional pyrometallurgical and hydrometallurgical techniques (Ma et. al., 2016; Tesfaye el al., 2017). In most studies so far, bioleaching has been used to extracts metals using iron and sulfur oxidizing ability and acid formation of acidophilic bacteria from sulfidic ores, also a naturally occurring acid mine drainage source. In the view of engineering perspective, the bioleaching processes could be defined as the ferric iron leaching. Environmentally speaking, it is an extremely efficient leaching process due to its high extraction rate below boiling temperature from room temperature to the 70 °C in the weak acidic media. This leads to an overall reduction in the needed energy and makes for a holistically eco-friendlier process.

Heap bioleaching of ores offers an excellent example of this process. During bioleaching, the leaching solution takes weeks or months, depending on the ore, and can maintain its economic feasibility since thousands of tons of low-content ore can be processed simultaneously in heap leaching. Most of the research about heap bioleaching as it relates to PCBs is, unsurprisingly, focused on gold and copper recovery. Copper extraction performs via biogenic ferric iron with iron-oxidizing bacteria (Panda et al., 2013). On the other hand, extracting gold requires the use of cyanogenic bacteria or fungi. These days, technological novelty focus on how to best upscale and optimize the methods of copper extraction; the goal is to increase the rates and yields of this bioleaching process.

For instance, Hubau, et al. (2020) suggested formation and separation of biogenic ferric iron from the actual leaching using continuous two-phase reactor. The recovery of Cu was over 96%; this result is superior to the results of previous projects. Other contemporary studies tend to use ground PCB and their waste powders, but there is also a much different approach. They proved that copper extraction from larger pieces of PCB is also possible, thanks to bioleaching as a mechanical pretreatment that allows for the avoidance of comminution. However, this study underlined the importance of population, showing that since depopulated PCBs were used, no conclusions could be drawn about the reactions of ECs (Adhapure, et al., 2013). Another study found that with the production of ferric iron via bio-oxidation and followed by a treatment of the filtered solution on the solder, the SnAgCu could be leached successfully. However, these results did not extend to the solder of SnPb.

Based on these previous two studies, the current research seeks to propose a new way to perform e-waste bioleaching. The current study aims to apply bioleaching solutions to the need for dismantling ECs: the resulting process is called "bio-dismantling." It makes use of iron oxidation by iron-oxidizing bacteria, and it is proven in the experiments presented here. Additionally, this study offers component fractions, which opens up a perspective for the fundamental waste PCB' mineralogy (Fig. 3). A new bio-dismantling technique is proposed using bioleaching technology, which will reduce costs by utilizing bioleaching, as well as reduce environmental impact (Monneron-Enaud et al., 2020). *Acidothiobacillus ferrooxidans* dominant mixed culture below pH 1.8 at 30 °C was used for bioleaching with 20 mM ferrous iron sulfate during 20 days. Bioleaching was also caused to the production of low-cost ferric iron by bacterial oxidation. Almost all the iron was precipitated as a brown precipitate in bio-dismantling solution. Another advantage of this process was the separation of relatively high grade components compared to the grinding process. This can expand current horizons as they apply to the recovery of high-concentration critical metals, especially as they are first enriched by dismantling and then being sorted (Panda and Akcil, 2021).

And before diving into the details of bioleaching techniques used in processing e-waste, Table 1 shows the bioleaching advantages and disadvantages comparing to other conventional leaching methods.

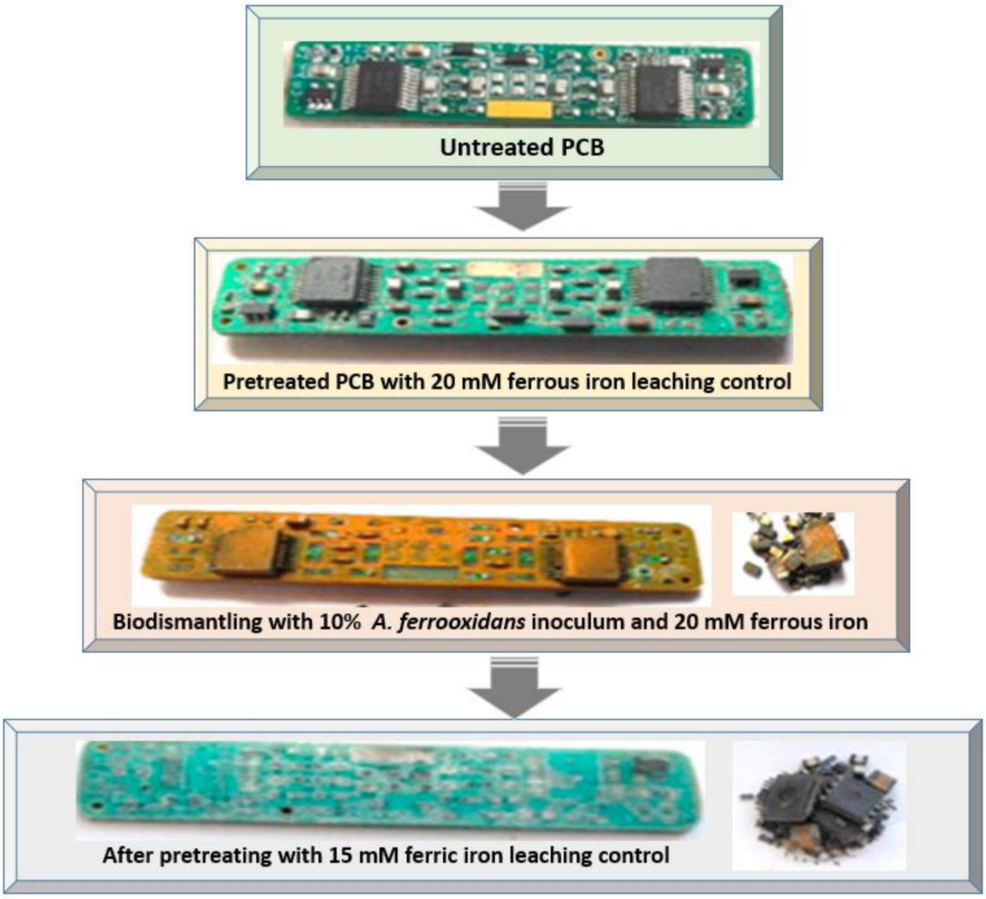

Fig. 3. Bio-dismantling of PCBs (redrawn and modified from Monneron-Enaud et al., 2020)

2. E-waste bioleaching

20 years ago, acidophilic microorganisms were first used in the bioleaching with PCB from electronic wastes (Brandl et al., 2001). As known that ferro-oxidising bacteria significantly increases Fe(III) regeneration, sometimes dramatic decreases seen in the bioleaching efficiency in the case of sufficiently toxic to acidophilic cultures (Hubau, et al. 2018; Magoda and Mekuto, 2022). Therefore, feasibility of PCB bioleaching is more important and needs to focus, etc. Therefore, bioleaching was discussed in details in the three parts: PCBs, spend battery and LCD/LED Panels.

Table 1. Simply comparison of the leaching techniques

Leaching Technique	Advantages	Disadvantages
Bioleaching (Brierley, 2008)	- Environmentally friendly - Lower energy consumption - Selective extraction - Can process low-grade ores - Can operate at ambient temperatures	- Slower leaching rate - Requires longer processing time - Limited to certain mineral types - Microbial contamination
Acid Leaching (Keskinen & Riekkola-Vanhanen, 2018)	- Fast leaching rate - Widely applicable - Can process high-grade ores - High metal recovery	- High energy consumption - Generates large volumes of toxic waste - Requires pH control and neutralization - Environmental impact
Heap Leaching (Petersen, 2019)	- Simple operation and low cost - Suitable for large-scale operations - Applicable to low-grade ores< - Reduced water consumption	- Slow leaching rate - Limited control over leaching conditions - Risk of acid and metal contamination of groundwater - Potential for heap instability
Pressure Leaching (Rao & Natarajan, 2001)	- High leaching rate - Increased metal recovery - Can process complex ores - Allows for higher operating temperatures	- High capital and operating costs - Requires corrosion-resistant equipment - Complex process control - Environmental concerns with high-pressure vessels
In Situ Leaching (Kordosky, 2017)	- Minimal surface disturbance - Reduced waste generation - Lower energy consumption - Suitable for deep-seated ores - Reduced water usage	- Limited to certain ore types - Difficult to control leaching conditions - Potential for groundwater contamination - Regulatory and public acceptance challenges

2.1. Used Printed Circuit Boards (PCBs)

First biological leaching experiments was its use in the separation of copper in TV circuit boards. Acidophilic mesophiles was used in these bioleaching experiments. The efficiency of this process especially was originally seen as dependent on the presence of the soluble iron present in the environment due to the driven force of the ferrous iron oxidation However, the recovery of metals succeeds with, a promising alternative, bioleaching by *Acidithiobacillus ferroxidans* (*A. ferroxidans*) for waste PCBs (Brandl et al., 2001, Choi et al., 2004, Wang et al., 2009). *At. Ferrooxidans* was used in small, lab-scale shake flask experiments; the main goal was extracting copper from PCBs (Bas et al., 2013). Same acidophilic bacteria were also used and obtained better results by adding Sulphuric acid for the metals leaching efficiency. Second order kinetic model obtained for H ion consumption altered to the shrinking core model after adding acid and precipitation of elemental sulphur oxidizing to sulphuric acid (Yang et al., 2014).

When we examine the bioleaching studies of PCBs, we see that they mostly remain at the small laboratory scale at the research level. These studies uses shaker bottles (Adhapure et al., 2013; Arshadi and Mousavi, 2015; Guezennec et al., 2015; Bryan et al., 2015) and stirred tank reactors (STR) larger than 1 L (Ilyas and Lee, 2014; Mäkinen et al., 2015; Guezennec et al., 2015; Xia et al., 2017; Hubau et al., 2020; Tapia et al., 2022), column (Chen et al., 2015), bubble column (Hubau et al., 2018), pulsed plate column (batch and sequential batch mode) (Jagannath, et al., 2017), continuous mode bioreactor with two-stages (Hubau et al., 2020), and stirred tank bioreactors at different volumes such as 2 L batch and 50 L batch and continuous STR (Akbari and Ahmadi, 2019).

More recently, mechanical activation has been proposed in an effort to enhance the efficiency of bioleaching with *At. Ferrooxidans* when it comes to extracting precious and base metals from waste PCBs (WPCBs). Cu, Ni, and Zn's extraction rates can be increased via mechanical activation; Erust et al. (2021) found that activated WPCBs yielded about 20% more than their un-activated counterparts. Akbari and Ahmadi (2019) developed another recycling strategy for decreasing sulphidic tailing together with e-wastes. Figure 4 gives the flow-sheet of the suggested two-step bioleach-solvent extraction processes. A mixed culture was prepared both Iron- and Sulphur-oxidizing microorganism for Cu-Ni-Co bearing tailing bioleaching. After 10 days, loaded solution containing 2.8 g/L of copper extracted with the appropriate extractant (LIX 984N in kerosene). Here, bioleaching experiments were performed using moderately thermophilic microorganisms (*Acidithiobacillus caldus*, *Leptospirillum ferriphilum*, *Sulfobacillus thermoSulphidooxans*, and *Ferroplasma*) growth in a Norris nutrient medium containing 0.5 g/L $MgSO_4$, 0.4 g/L $(NH_4)_2SO_4$, 0.4 g/L K_2SO_4 and 0.29 g/L $CaH_4(PO_4)_2$ at 45 °C. As can be seen in Fig.4, it is remarkable that 96% copper was obtained after suggesting the two-stage process flow sheet.

Wei, et al. (2020) enhanced bioleaching by applying a targeted DC electric field actually enhanced bioleaching. In this study, a bioelectric reactor used to recovery of copper was enhanced the bacterial growth and their activity, which in turn lead to more effective ferrous iron oxidation. In the bioleaching process for Pb, Ni, Cu, and Zn, *Acidiphilium acidophilum* (*A. acidophilum*) was used in tandem with the original pure culture of *At. Ferrooxidans*. Another acidophilic culture, *Sulfobacillus benefaciens* and mainly *Leptospirillum ferriphilum*, was also used to oxidize iron in adapted growth medium containing waste PCB (Hubau et al., 2020). Growth medium is obtained with 0.4 g/L $(NH_4)_2SO_4$, 0.81 g/L H_3PO_4, 0.48 g/L KOH, and 0.52 g/L $MgSO_4.7H_2O$ moreover FeSO4.7H2O added for 3 g/L of Fe(II) with adjusting pH 1.2 with H_2SO_4 (Anaya-Garzon et a., 2021). In addition to the exponential growth of cultures in PCB media, the inhibitory effect of PCBs on bacterial activity with the delay observed in biooxidation phase of Fe(II). In batch mode, the adaptive bacteria oxidized 8 g/L iron in the presence of a PCB leachate equivalent to 6% PCB, representing 6 times of the metal content, shortened the inhibition limit by up to 2.5 times and enhanced microbial oxidation of iron with sequential sub culturing before running in the continuous mode (Anaya-Garzon et a., 2021).

Pourhossein and Mousavi (2023) presented a novel eco-friendly method treating spent PCBs using biogenesized thiosulfate (Bio-Thio) obtained from Acidithiobacillus thiooxidans cultured medium. The effective concentrations of inhibitor and pH (NaN3: 3.25 mg/L and pH= 6–7) has led to the highest bio-production of thiosulfate (500 mg/L).

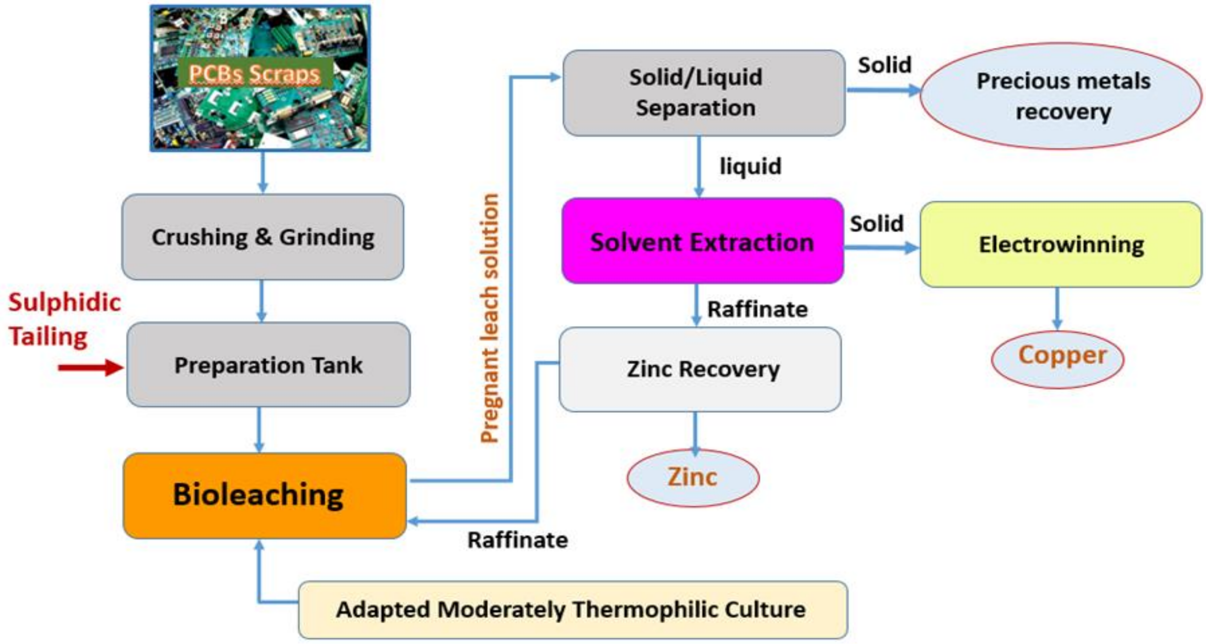

Fig. 4. The flow sheet of moderately thermophilic microorganisms bioleaching and SX of PCBs scraps and sulphidic tailing (redrawn and modified from Akbari and Ahmadi, 2019)

Other heterotrophic species, including *Acinetobacter sp. CrB2* were also used to extract copper via bioleaching. The ability of producing extracellular enzymes (protease enzymes, amylases, and cellulases) and by-products of the metabolic activities of species were competed, and increased the overall efficiency of the bioleaching process. In some specific optimized conditions, certain indigenous cyanogenic bacterial strains which were taken and isolated from the landfills (e-waste) have potential to serve as copper extractors. In addition, Bacillus sp. which are isolated from the sponge cells (*Hymeniacidon heliophile*) have recently also shown the potential to act as a copper-extracting microorganism, especially forming nanoparticles (Rozas et al., 2017). This is the result of peptides which are released by the bacteria; the peptides leach the copper, absorb the copper ion, and then incorporate the ion into their own cells. The result is copper nanoparticle formation.

In addition to different types of bacteria, there are also several fungal strains that are useful for e-waste metal extraction. Fungi strains secrete many different organic acids, amino acids, and metabolites that cause metal dissolution. Such metabolites by fungi can exchange metal ions and hydrogen ions, or form soluble metal complexes and chelates. This then leads to metal dissolution. These days, *Penicillium simplicissimum* (*P. simplicissimum*) is being researched as a means of extracting both copper and nickel (Esmaeili and Arshadi, 2022). Other effective parameter, carbon sources addition (sucrose, sugar, chees whey, and cane molasses) were also discussed, and the researchers learned that these unconventional carbon sources actually enhance the bioleaching process. In addition, the researchers used mixed fungal cultures to extract metal from e-waste. They posit that the microorganisms are gradually adapting and becoming tolerant to the heavy metals. These microorganisms which are tolerant to heavy metals can then be used in large scale industrial projects. Species belonging to the genus *Penicillium* and *Aspergillus* such as *Aspergillus foetius* (*A. foetius*) and *Penicillium funiculosum* (*P. funiculosum*) are two such existing microbes.

2.2. Spent batteries

There are many different types of batteries, including alkaline batteries derive energy from the reaction between Ni-Cd, Ni-H, Zn-Mn, and Zn-C as well as nowadays rechargeable battery lithium-ion batteries (LIBs), all of these models are popular in today's market.

When it comes to alkaline batteries, many autotrophic acidophiles have been found to be effective in the leaching of the metals. Popular species of iron oxidizing bacteria *At. Ferrooxidans* has been used to the recovery of metals from Ni-Cd batteries with success. In other studies, *At. Ferrooxidans* has also been used to recover zinc and manganese metals from depleted alkaline button-cell Zn-Mn batteries. In studies at an initial pH of 2, at 30 °C and a pulp density of 10 g/L, which lasted for 21 days, Zn and Mn were efficiently extracted with the concentrations of 53% and 99%, respectively.

In a similar study using the same bacterial strains, it was proved that the 100g/L pulp density of depleted NMC batteries, 90% of Ni, 82% of Mn and 89% of Co dissolution could be achieved after 3 days of leaching. In addition, it showed successful application of heterotrophic fungus in the metal extraction process for these kinds of batteries. Heterotrophs, mostly *Aspergillus* and *Penicillium spp.* were investigated (Asghari et al., 2013; Pathak et al., 2021; Shah et al, 2020) Still more studies display the effectiveness of the *Aspergillus* species when it comes to dissolving metals in Zn-Mn and Ni-Cd types of batteries. In order to confirm these findings, a comparative study was conducted. It looked at the results of bioleaching using *A. niger* for Ni-Cd batteries and compared three different synthetic broth media of Potato Dextrose (PDB), Malt Extract (MEB) and Richards (RB). The most effective process turned out to be a two-step bioleaching process with RB as the medium; It is noteworthy that the present Ni and Cd metals in the batteries were dissolved in 21 days with a yield of 81.41% for Ni and 92.31% for Cd.

In addition to its application with alkaline batteries, lithium-ion batteries (LIBs) are now a hot topic in the field. Mishra et al., (2008) presented that acidophilic bacteria can be used to dissolve metals from cathode of LIBs, only need of elemental sulfur and iron as energy sources in a growing medium. There has been a lot of research in recent years that looks at metal extraction from depleted LIBs through the use of both autotrophic acidophiles and heterotrophic microorganisms. One comparative study featured on the spend LIBs with a fungi and autotrophic acidophilic bacteria with their specific medium and *At. thiooxidans* found more effective than of *A. niger* (MM1 and SG1) at dissolving these metals than its bacterial leaching counterpart. The researchers reported the dissolution of cobalt and lithium were achieved with 82% and 100%, respectively. Moreover, their method has been summarized schematically in Fig. 5. Additionally, researchers learned that the secret to more efficient bioleaching includes optimizing the bioleaching parameters by using *A. niger* for metal extraction from LIBs. They also proposed the optimization of bioleaching parameters through the use of heterotrophic bacteria, including *Gluconobacter oxydans* and *Aspergillus nomius*. Heterotropic bacteria and fungi also caused to high recovery of metal ions by producing various organic acids (Roy et al., 2021).

Yet other studies show that using autotrophic mesophilic bacteria such as *At. ferrooxidans* can lead to more efficient metal extraction from depleted LIBs. One study suggested that 40 g/L of bacterium concentration was dissolved in 12 days and quite an effective bioleaching results were obtained with Li: 100 %, Co: 88 %, and Mn: 20 %. Researchers also explored higher pulp density (5 g/L) of mesophiles and moderate thermophile (*L. ferriphilum* and *S. thermosulfidooxidans*) and its impact on the leaching of spent LIBs. After 1.5 days of bioleaching at 42°C, 98.1% Li and 96.3% Co were successfully obtained (Horeh et al., 2016).

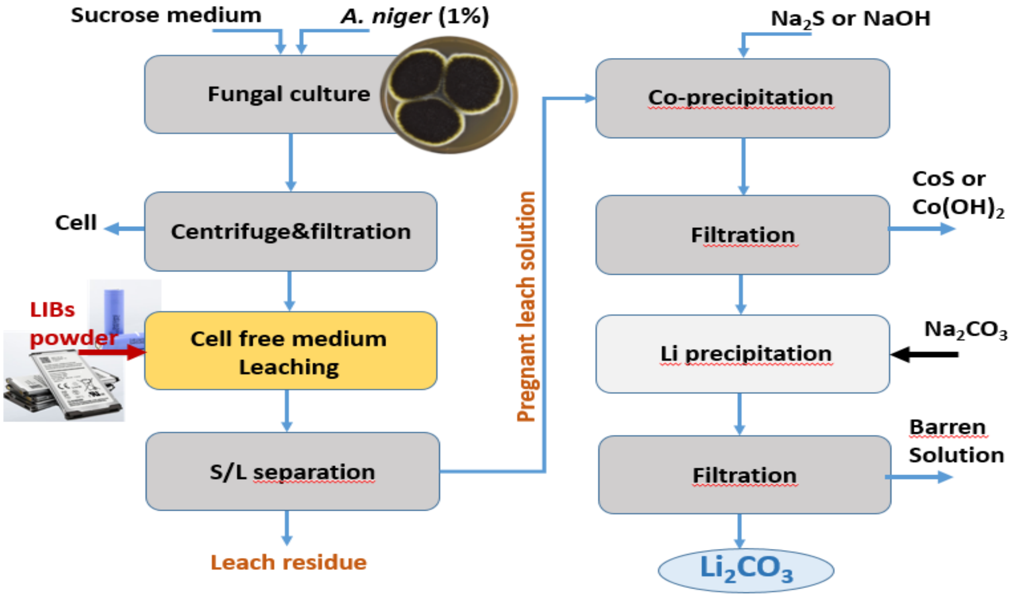

Fig. 5. Bioleaching of LIBs with A. Niger (redrawn and modified from Biswal et al., 2018)

2.3. Used LCD/LED Panels

Much of the research involving bioleaching Liquid Crystal Displays (LCDs) on recovering Indium and Gallium (De Oliveira et al., 2021). *At. ferrooxidans* and *At. thioxidans* were used to extract indium and tin from LCD panels. Researchers were especially used adapted acidophilic bacteria. The most efficient results 55.6% indium and 90% tin recovered (Willner et al., 2018). Moreover, in addition to these acidophilic bacteria, other heterotrophies such as A. niger have also shown to improve the fermentation method, which resulted in more effective leaching of indium from LCD panels. With this improved method, the efficacy of indium bioleaching increased from 12.3% to 100% (Cui et al., 2021); it can be said that carboxyl groups from organic acids and/or proteins, which are critical in the release of H+ ions necessary for the dissolution of indium, are effective.

In addition to LCDs, light-emitting diodes (LEDs) are also an up-and-coming topic in the field, especially as they are secondary resource of metals. These heavy metals are also having an environmental risk, since their components are filled with pollutants. As a result, many studies focus on the recovery of metals from LEDs. One such study resulted in the development of a new approach called two-stage indirect-bioleaching; it relies on adapted cells of *At. ferrooxidans* (Pourhossein and Mousavi, 2018). Also the addition of biogenic ferric was improved the efficacy of the bioleaching at 4-5 g/L of pulp density. This study shows that a direct (i.e., not stepwise) bioleaching approach actually results in a low yield of metals and materials. Plus, with the increased pulp density from 5 to 20 g/L, the metals tolerance of *At. Ferrooxidans* decreased (Pourhossein and Mousavi, 2019), All this notwithstanding, the adapted cells ended up with higher Fe3+ level, cell number, ORP, as well as lower pH when compared to the non-adapted cells. So, this adaptation led to more efficient leaching of metals (%): Cu: 84, Ni: 96, and Ga: 60.

On the other hand, displays based on previous generation liquid crystal displays (LCDs) are cathode ray tubes (CRT-based TVs) which contain phosphorus. The most concentrated elements in phosphorus powder are Yttrium, zinc, lead and silicon (Ferella et al., 2017). Fluorescent phosphor powders are also collected waste in the recycling of fluorescent bulbs and energy saving (compact fluorescent lamps). Specific strains can be used to recovery and selective separation of REE. For example; Reed et al. (2016) used Gluconobacter oxydans strain after 9 days of leaching, 12% efficiency of total Y, La, Ce, Eu, and Tb were leached from spent phosphor powder. Hopfe et al. (2017) also extracted REEs during 14 days and selectively separated 12.6% for Y from total La, Ce, Eu, Gd and Tb in spend phosphor powder, when *Zygosaccharomyces lentus* and *Komagataeibacterhansenii* strains were used. *Kombucha*-consortium with 7.9% REE, *Komagataeibacter xylinus*, *Lactobacillus casei*, and *Yarrowia lipolytica* for Y and Eu (up to 12.6% REE) were compared (Sethurajan, 2019).

3. Bioleaching mechanisms for valuable metals recovery

Apart from the conventional processes, microbial methods in many biotechnological processes have been performed since prehistoric times. Microbial leaching, especially Copper leaching applied for mine waters known since the Greeks and Roman periods may be more than 2000 years ago (Bosecker, 1997). Microbial leaching, direct and indirect oxidation play a major role in metal mobilization. Since 1964, the release of metals via these types of biochemical oxidation reactions are known (Silverman and Ehrlich, 1964). In direct bacterial leaching, it is enzymatically catalysed after physical contact between the bacterial cell and the mineral surface. Although the mechanism of attachment and how metal solubility begins is still not fully understood, bacteria prefer certain crystal-defective regions without adhering to the entire mineral surface, and metal solubility results from electrochemical interactions. For example; copper bioleaching by *A. ferrooxidans* from waste PCBs was mainly based on direct oxidation of elemental copper through the prior biooxidation of ferrous ions. (Choi et al., 2004, Liang et al., 2013). On the other hand, indirect bioleaching occurs when the bacteria generate a lixiviate (leaching agent) which chemically oxidizes the mineral. The interaction between *A. ferrooxidans* cells and 500–1000 µm particle sizes of PCB particles was suspected to be positive if the van der Waals attraction force was greater than the electrostatic repulsive force that could only occur at high ionic strength of the solution (Işıldar et al., 2019). When the bonds between the metal ions and ligands in the e-waste are stronger than the lattice bonds between the metal ions and the solid particles, the bioleaching process is successful and the metal is successfully leached from the solid particles. Another critical parameter is initial pH. Since waste PCBs are alkaline, acidic microbial leaching environment rapidly changed after adding PCBs. In growing media, acidic conditions focusing on the Eh-pH variations also known as Pourbaix diagramme should inhibit of hydrolytic reaction of Fe^{3+}(Lin et al., 2021). Low pH could also cause to high stronger bacteria in order to oxide Fe^{2+} to Fe^{3+}. Moreover, waste PCBs consist of various mixed metals in the growth environment also affect the metal reactivity from Aluminium to Copper, since the recovery of metal is depending on its reactivity. The faster and efficient leaching will result of stronger reactivity.

On the other hand, it should be remembered that different from conventional ore leaching, bioleaching of secondary raw materials, including e-waste uses heterotrophic and autotrophic bacterial cultures. Three main mechanisms could be classified for bioleaching of metals from e-waste: Acidolysis, redoxolysis and complexolysis. Protonation of oxygen atoms on the surface of the metallic compound is Acidolysis. There are many heterotrophs that are capable of performing acidolysis, including biogenic organics (such as citric acid, succinic acid, oxalic acid, formic acid, gluconic acid, and pyruvic acid) and some inorganic acids (like H2SO4) (Mishra et al., 2021). Redoxolysis involves reactions with the oxidation-reduction in order to boost metal solubility; it also increases the energy transfer that is necessary as the microbe grows. The complexolysis mechanism comprises the system in which fungi and cyanogenic bacteria generate cyanide During the late stationary phase, decarboxylation of glycine takes place. Fig. 6 presents for a mechanism and the microbial mode of action for e-waste (Mishra et., 2021).

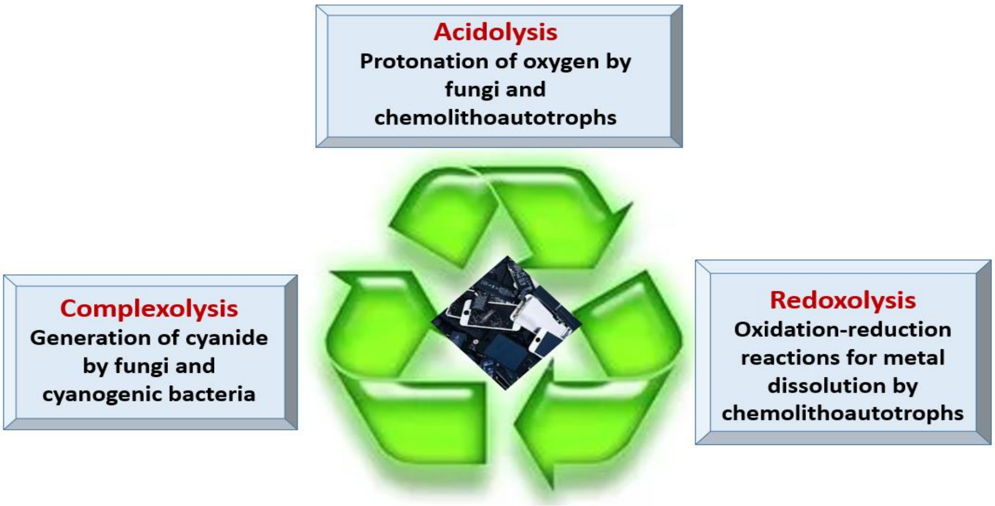

Fig. 6. Mechanism for microbial leaching of metals from e-waste (adapted from Mishra et., 2021)

3.1. Bacterial mechanism

Many investigators have carried out studies about bioleaching, specifically related with acidophilic species, *At. ferrooxidans* and *At. thiooxidans* (Smith, J., Johnson, A., & Brown, K. 2022) These studies have shown that there needn't be any contact between the bacteria and the surface of e-waste powder (Mishra et al., 2021). Throughout this bioleaching process, the oxidation reaction (i.e., the process of converting Fe^{2+} to Fe^{3+}) occurs via inorganic acid and enzymes; thus, physical contact is not necessary (Sukla et al., 2015). The overall rate of reaction in improved as the H+ ion is produced throughout the oxidation process. All this notwithstanding, when *At. ferrooxidans* and *At. Thiooxidans* are used in the bioleaching process, significant results are still achieved. Rate of Fe^{2+} oxidation, pH, amount of Fe^{2+}, all play a crucial role in the overall efficacy of the bioleaching process. Although the chemical oxidation at low pH, from converting Fe^{2+} to Fe^{3+}, is very slow, acidophilic culture increases faster biooxidation at least 105-106 times (Ghassa et al., 2017).

While researchers have been able to pinpoint the importance of these factors, the bioleaching process has yet to be totally understood (Glazer and Nikaido, 2007). E-waste lacks its own energy source: for this reason, supplementary iron and elemental sulfur must be included in the medium, usually in the form of ferrous sulphate and elemental Sulphur. These additives contribute to the high redox potential of the medium, as well, which can ultimately make the indirect leaching possible.

The three important steps of the bioleaching process are:

- oxido-reductive reactions,
- secretion of organic and inorganic acids
- release or excretion of microbial metabolic products, complexing agents and chelators.

The aforementioned redox reactions occur on bacteria known as the exopolysaccharide layer. Several exopolymeric substances such as polysaccharides, proteins, amino acid, and lipids are discharged from the bacteria, and these also important roles throughout the process. To be able to enhance dissolution efficiency as well as metal recovery, the interactions or affinity between microbe and substrate are crucial. Continuous acid (H_2SO_4) and Fe^{2+}/Fe^{3+} cycle could improve efficient approach. The metal bioleaching when combined acidolysis-redoxolysis reactions:

Microbial: $S^o + 1.5O_2 + H_2O \rightarrow 2H^+ + SO_4^{2-}$

$$4Fe^{2+} + O_2 + 4H^+ \rightarrow 4Fe^{3+} + 2H_2O$$

Chemical: Cu^o (e.g., in e-waste) + $2Fe^{3+}$ (biogenic) $\rightarrow Cu^{2+} + 2Fe^{2+}$

Cu^o (e.g., in e-waste) + H_2SO_4 (biogenic) + $0.5O_2 \rightarrow Cu^{2+} + SO_4^{2-}$

3.2. Fungal mechanism

Fungi naturally produce of biogenic cyanide or organic acids are key initiators of precious metal recover from e-waste materials, since the organic acids such as oxalic acid, tartaric acid and citric acid are natural chelating and complexing agents. Organic acids are also notable for being biodegradable and less corrosive than inorganic acids. Depending on their pKa values, dilute solutions of carboxylic acids are moderately acidic in the pH 3-5 range. Fungi can tolerate toxic metals as they can grow in a wide pH range (Santhiya and Ting, 2005). Biocyanidation for example of A. niger can be sustainable alternative in the extraction of Au and Ag extraction (Wang et al., 2021). Fungi Also, fungi (*A. niger*) produce organic acids (e.g., gluconic acid and citric acid) with the following reaction;

$$C_6H_{12}O_6 + 1.5O_2 \rightarrow C_6H_8O_7 + 2H_2O$$

Such leaching operations are possible under both aerobic and anaerobic conditions; other factors such as temperature, pulp density and pH also play a role in determining the efficacy and efficiency of a given bioleaching undertaking.

Overall, bioleaching is done with fungi and bacteria, and its efficiency leans heavily on factors i.e. the composition of growing media, its pH, e-waste surface area and their particle sizes; the main goal of this process is to recover metals from e-waste materials. There are many different microorganisms that have been shown efficient recovery from e-waste, both bacteria and fungi, i.e. *A. niger*, *At. Thiooxidans*, and *Aspergillus nominus* (*A. nominus*).

4. Future prospects and conclusions

Throughout the past several years, there has been a lot of research on the topic of recycling electronics and properly addressing electronic waste. As discussed previously, the increasing scarcity of mineral resources around the globe and the related environmental problems motivate the scientific and engineering community to seek new and more effective ways to reduce waste and promote recycling. It's important to highlight the role of recovering these precious materials as recycling becomes more mainstream and effective. Certification for waste electrical and electronic equipment (WEEE) and batteries is a significant step forward in addressing this worldwide issue (Eurostat, 2020; Cucchiella et al., 2015).

In light of all this, it is crucial to resolve the disadvantages of the bioleaching process as laid out in this paper. Further research could focus on reducing the leaching time and increasing the pulp density. Researchers should also continue to study the comparative efficacies of different microorganisms, as well as the effects of contamination on these microorganisms. In addition to these, there are further fields of e-waste recycling that researchers have yet to fully explore, including materials extractions from solar panels and other energy-related e-waste. It's important to keep these issues in the forefront, lest we forget their technological, environmental, and economic impacts.

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