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# Biohydrometallurgy: paving the way for a greener future of mineral processing in Indonesia - A mini review

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ABSTRACT

Biohydrometallurgy, a technology that employs microorganisms for metal extraction, has existed since the 1960s. As environmental regulations tighten and the quality and complexity of available ores for processing decline, this technology offers an alternative for mineral processing. Several countries, including South Africa, Russia, Chile, Australia, the United States, China, Burma, New Zealand, Peru, Uzbekistan, and Ghana, have used this method commercially in copper processing plants and gold and silver processing plants. In Indonesia, this method has not been developed or applied industrially. Given the challenges of limited capital and low-grade ore processing in the future, proposing biohydrometallurgical processing in Indonesia is worthwhile. Globally, biohydrometallurgy has become a significant area of research focus. In Indonesia, however, the investigation of biohydrometallurgy is primarily conducted at the Bandung Institute of Technology (ITB). This specific line of investigation was initiated in 2009, with an emphasis on extracting nickel (Ni) from laterite ores. Additional investigations have been undertaken to explore the extraction of metals including copper (Cu) and gold (Au). This review paper also summarizes ongoing laboratory-scale studies encompassing the extraction of lead (Pb), zinc (Zn), silicon (Si), magnesium (Mg), silver (Ag), rare earth elements (REEs), lithium (Li), strontium (Sr), phosphorus (P), potassium (K), calcium (Ca) and the application of phytomining technology and coal biomining. The research outcomes to date present a promising and potentially scalable perspective that could be advanced to pilot plant implementation and industrial application within Indonesia.

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## 1. Introduction

Metals can be extracted and recovered using microorganisms in a method known as biohydrometallurgy. This technique can be used to metal ores, concentrates, and wastes (Schippers et al., 2013; Johnson, 2014). In biohydrometallurgy, there are two commonly used terminology: bioleaching and biooxidation. Bioleaching refers to extraction procedures involving the dissolution of valuable metals such as copper, zinc, nickel, cobalt, and uranium (Brandl, 2001). In contrast, a different term—biooxidation—is used exclusively in the gold processing industry as a pre-processing technique for refractory gold ore or concentrate. In cyanidation, microorganisms can oxidize sulfide minerals, liberating the trapped gold particles (Rawlings, 1997). Since *Acidithiobacillus ferrooxidans*, an iron and sulfur-oxidizing bacterium, was discovered in acid mine water in 1947, the biohydrometallurgical technique has been widely used (Colmer and Hinkle, 1947).

In 1958, the Kennecott Bingham Mine in Utah received a patent for the bacterium, which was then employed to process low-grade copper ore heaped up to a height of one hundred meters (Brierley, 1997; Brierley, 2008). Nonetheless, the decade of the 1980s marked the beginning of a period of fast development in biohydrometallurgy. The Lo Aguirre Mine in Chile was the first commercial copper bioleaching application, and it began producing cathode copper in 1980, with an annual production of 16,000 tons (Olson et al., 2003). Biohydrometallurgical techniques have been effectively implemented in the mining sector in recent years to economically extract base and precious metals from ores or concentrates (Brierley and Brierley, 2013). In 1986, the biooxidized refractory gold concentrate was successfully commercially operated at the Fairview Mine in South Africa, and it is still in operation today (Olson et al., 2003; Van Aswegen et al., 2007). Even though many studies and investigations are ongoing, biohydrometallurgical studies and applications remain extremely low in Indonesia. The continuous mining of natural resources leads the availability of high-grade mineral deposits to become increasingly scarce, leading to an increase in the quantity of ore that is low-grade, complicated, and difficult to process. Biohydrometallurgy is the method of choice for processing sulfide ores and refractories. Compared to conventional extraction techniques (hydrometallurgy and pyrometallurgy), this technology has lower investment costs and is friendlier to the environment (Brierley and Brierley, 2013).

This paper aims to bring biohydrometallurgy to industry and academia as a process option that is more ecologically friendly than existing conventional approaches. This review includes the challenges and factors driving the development of biohydrometallurgy, bioleaching and biooxidation mechanisms, current biohydrometallurgical technology, commercial biohydrometallurgical plants, and conclusions regarding biohydrometallurgical applications in Indonesia.

## 2. Biohydrometallurgical benefits and challenges

Using biohydrometallurgical techniques to recover metals involves a number of intriguing variables. The biohydrometallurgical process uses microorganisms that can oxidize iron and sulfur (sulfide ore) as a source of nutrition to oxidize iron to become an oxidizing agent in the leaching process and sulfur compounds to sulfuric acid, which leaches precious metals like copper, nickel, zinc, cobalt, and others. Furthermore, microorganisms produce metabolic products such as organic acids or biosurfactants that can extract metals, allowing them to be employed in processing sulfide or oxide ores. Biohydrometallurgical techniques offer many benefits, including:

a. It can be used to recover metals in conjunction with or instead of a concentration process. The concentration method reduces bioleaching/biooxidation feed to lower biohydrometallurgical capital and operational expenditures. Nevertheless, biohydrometallurgical techniques can also be used without a concentration process, for instance, to treat low-grade ore or oxide ores.
b. Biohydrometallurgical processing is adaptable from small-scale to industrial mining due to its versatile production capacity. Biohydrometallurgical methods are scalable. Copper bioleaching has been used on an industrial scale, with ore throughputs ranging from 1,500 to 130,000 tons per day (Neale et al., 2011).
c. High-quality metals can be produced at the mine without a separate smelting facility. This condition makes the biohydrometallurgical process more cost-effective by reducing transportation, eliminating the need to pay royalties for NSR (Net Smelting Return), and eliminating the need to pay penalties for metal impurities.
d. The biohydrometallurgical process generates acid either through the oxidation of minerals or the metabolism of microorganisms. As a result, the cost of the required leaching reagents (acid) is significantly reduced.
e. Because the biohydrometallurgical process is often carried out at temperatures ranging from 20 to 80 °C using bio-heap leaching or agitation leaching, the costs of the process are substantially lower.
f. It can process low-grade ores economically because the process costs, including those for energy, reagents, and waste treatment, are lower than those required by conventional methods.
g. The biohydrometallurgical method is less harmful to the environment. Because microorganisms can renew the leaching reagents, such as sulfuric acid and organic acids, the number of chemical reagents required for the leaching process can be reduced, which in turn lowers the cost of the process. Sulfur in the ores is also transformed into $SO_4^{2-}$ ions. The oxidation of arsenic results in the formation of arsenic compounds that are stable in solid form and have a low toxicity level.

Indonesia faces various obstacles to applying this biohydrometallurgical process technology on a large scale, including:

a. Although the biohydrometallurgical process has been utilized in many countries, it has not yet been implemented in Indonesia. The biohydrometallurgical process is a relatively new technology compared to conventional approaches; hence, funding and research are required to investigate this process in depth and ensure that it can be successfully implemented in Indonesia.
b. Like their hydrometallurgical counterparts, biohydrometallurgical processes are highly tailored operations, dependent on the nature of the minerals to be processed, the microorganisms employed, and the technique used. Hence, laboratory-scale research is required, followed by pilot plant-scale and industrial-scale studies.
c. This technique takes a longer processing time compared to the melting, pressure leaching, and roasting operations.

Biohydrometallurgical technology offers promising opportunities and formidable hurdles; its successful implementation in Indonesia depends on cooperation between academics, businesses, and the government.

## 3. Biohydrometallurgy in metallurgical processes

The metallurgical process, including mineral processing and metallurgical operations, involves several complex steps (Fig. 1), illustrating a simplified sequence of physical, chemical and biological processes employed to extract valuable minerals from the ore. Initially, the ore is mined: the extraction of ore from the earth through mining that can be performed through various methods such as open-pit mining, underground mining, placer mining, mountaintop removal mining, etc. The mined ore is then transported to the mineral processing plants. At this stage, the ore is subjected to comminution to reduce the size of the particles, a comprehensive process involving crushing, grinding, and sieving (Chaerun et al., 2020; Chaerun et al., 2020a; Mubarok et al., 2021). This procedure is designed to enhance the surface area for ensuing the subsequent separation processes and to liberate the valuable minerals entrapped within the gangue materials. The ore subsequently undergoes concentration using techniques such as gravity separation, magnetic separation, flotation, and flocculation (Ankireddy et al., 2023; Diab et al., 2022; Kabatesi et al., 2022; Sanwani et al., 2015a; 2015b; 2015c; 2015d; 2015e; 2016a; 2016b; 2017; 2020; 2021a; 2021b; 2022; Teniola et al., 2022; Wahyuningsih et al., 2020; Wahyuningsih et al., 2018; Zheng et al., 2022). These methods serve to separate the valuable minerals from the gangue. The outcome of this stage is a concentrate containing the desired minerals, and tailings, which constitute the waste materials.

The concentrated ore (concentrate) is then subjected to an extractive metallurgical process, such as pyrometallurgy, hydrometallurgy and biohydrometallurgy to extract valuable metals (Keane et al., 2023; Qin et al., 2022; Roberto and Schippers, 2022). After extractive metallurgy processes, the extracted metal is subsequently refined to further purify in eliminating impurities to achieve the desired level of purity for specific applications through techniques, such as pyrometallurgical refining and hydrometallurgical refining (Adnan et al., 2022; Dong et al., 2023; Iturrondobeitia et al., 2022; Neumann et al., 2022; Raabe, 2023; Sun, 2023). The selection of refining techniques is dependent upon several factors, including the inherent characteristics of the metal, the specific impurities that are present, and the intended use or application of the refined metal. Simultaneously, the management of tailings, which are the residual waste materials following mineral processing and the extraction of valuable minerals, as well as by-products from extractive metallurgy processes, is vital for mitigating environmental damage. Given that these by-products and tailings often retain significant quantities of valuable metals classified as low-grade materials, they present an opportunity for recycling into secondary metal resources. Such materials may be suitable for biohydrometallurgical extractive metallurgy processes, as the principles of biohydrometallurgy are particularly applicable to low-grade ores, metallurgical wastes, or complex ores where conventional methods may be less effective.

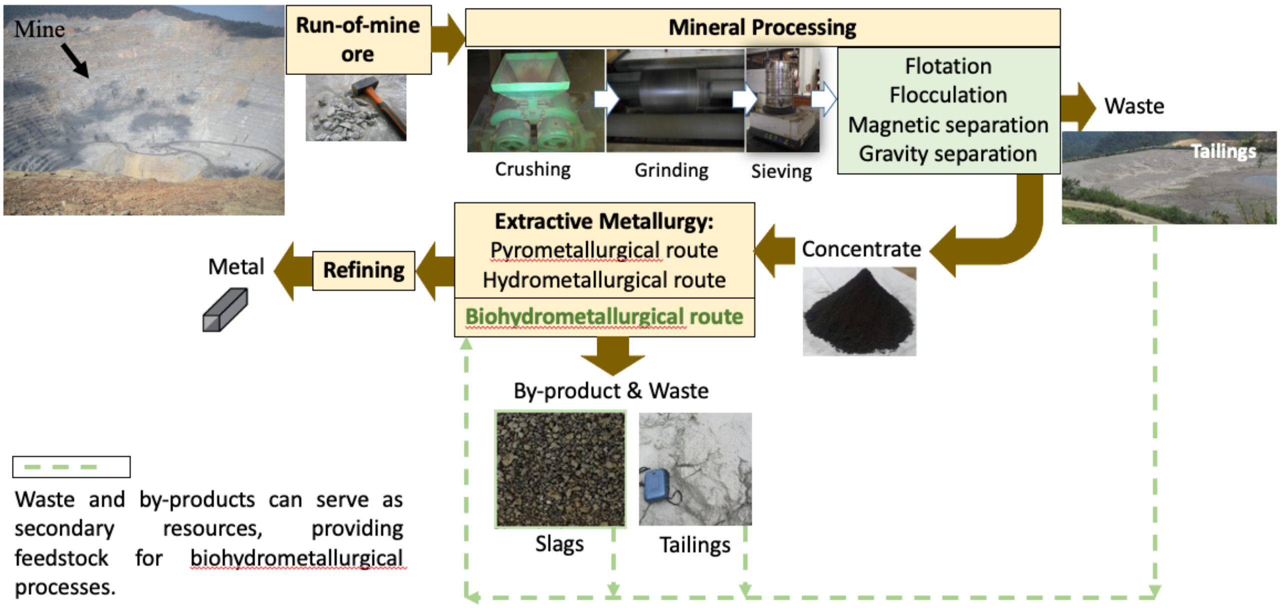


**Fig. 1.** A simplified sequence of operations in the metallurgical process, encompassing both mineral processing and metallurgical procedures. It specifically highlights the position of the biohydrometallurgical process within this chain of operations.

In addition, biohydrometallurgy is a subset of hydrometallurgy, one of the principal branches of metallurgy. Biohydrometallurgy is typically positioned in the extractive metallurgy, following the concentration stage and preceding the refining stage, in the overall metallurgical process. After biohydrometallurgy has been used to extract the valuable metals, they can be refined to remove any remaining impurities and produce the final metal product. Consequently, biohydrometallurgy is crucial to the extraction phase of the overall metallurgical process.

## 4. Mechanism of mineral oxidation by microorganisms

The biooxidation of sulfide minerals occurs through direct and indirect mechanisms (Silverman and Lundgren, 1959). Physical contact or direct interaction between bacterial cells and the sulfide mineral surface is involved in the direct mechanism. Bacteria bind to the sulfide mineral surface and catalyze the mineral's oxidation reaction, producing protons ($H^+$) and soluble metal sulfate. Meanwhile, the indirect mechanism involves ferric ($Fe^{3+}$) and ferrous ($Fe^{2+}$) ion cycles. $Fe^{3+}$ works as an oxidant, oxidizing metal sulfides before being reduced to $Fe^{2+}$. Bacteria then reoxidize $Fe^{2+}$ into $Fe^{3+}$. The chemical reaction of sulfide minerals is illustrated Eq. (1), (2), (3).

Surface passivation of carbon materials happens due to changes in the physical and chemical properties of the carbonaceous surface material. Certain microorganisms, such as fungi and heterotrophic bacteria like *Phanerochaete chrysosporium*, *Streptomyces setonii*, and *Trametes versicolor*, have been shown to passivate or carbonaceous breakdown material (Yang et al., 2013). Extracellular polymeric substances (EPS) produced by microorganisms can be adsorbed onto the surface of carbonaceous materials. Some microbes can release lignin-degrading enzymes and aromatic chemicals, which can break down carbon chains and degrade the carbon in the ore, reducing the preg-robbing of ore behaviour.

Direct mechanism : $$FeS_2 + O_2 + H_2O \xrightarrow{\text{bacteria}} Fe^{2+} + 2H^+ + 2SO_4^{2-} \quad \text{Eq. (1)}$$

Indirect mechanism : $$2Fe^{2+} + 0.5O_2 + 2H^+ \xrightarrow{\text{bacteria}} 2Fe^{3+} + H_2O \quad \text{Eq. (2)}$$

$$FeS_2 + 14Fe^{3+} + 8H_2O \longrightarrow 15Fe^{2+} + 16H^+ + 2SO_4^{2-} \quad \text{Eq. (3)}$$

## 5. Biohydrometallurgy mechanisms

The mechanism of redoxolysis in the bioleaching process involves the use of microorganisms to oxidize reduced metal ions into their soluble forms. This is done through the release of metabolic products such as hydrogen ions, electrons, and metal-oxidizing enzymes. The microorganisms, such as acidophilic bacteria, thrive in low pH environments and use sulfur and iron as electron acceptors to facilitate metal oxidation. The oxidation of metals results in the release of metal ions into the solution, which can then be recovered through various methods such as precipitation or electrowinning. This process increases the overall efficiency of metal extraction compared to traditional methods, making bioleaching an environmentally friendly alternative.

The mechanism of redoxolysis in the bioleaching process involves the oxidation of metal sulfides by microbial activity to release the metals as soluble ions. This is achieved through the production of oxidizing agents such as sulfur-oxidizing bacteria and ferric iron, which catalyze the oxidation of sulfide minerals. The resulting metal ions can then be recovered through conventional hydrometallurgical methods. Additionally, the metabolic activities of the microorganisms can also generate organic acids, which can contribute to the solubilization of the metals and further enhance the efficiency of the bioleaching process.

The mechanism of acidolysis in bioleaching process involves the use of acid-producing microorganisms to dissolve metal sulfides, leading to the production of sulfuric acid (Deviany and Chaerun, 2022). This acid acts as a catalyst for the oxidation of metal sulfides, resulting in the release of metal ions into solution. This process also results in the production of sulfur dioxide gas, which can be further oxidized to sulfuric acid, thereby enhancing the overall rate of bioleaching. Additionally, acidolysis can also involve the production of organic acids, such as citric acid, that can also contribute to the dissolution of metal sulfides. The acidolysis process in bioleaching is an important step in the extraction of valuable metals from mineral ores and concentrates. The mechanism of acidolysis in the bioleaching process involves the utilization of acid-producing microorganisms to solubilize metal ions from metal-bearing minerals. This is achieved through the secretion of organic acids, such as citric acid, which are capable of breaking down the mineral structure and releasing metal ions into solution. These metal ions can then be recovered through various physical or chemical processes for further refining or extraction.

## 6. Biohydrometallurgical technologies

### 6.1. Dump bioleaching

In the 1960s, the Kennecott Copper Corporation was the first to use bioleaching to recover copper from low-grade ore. It is currently the most cost-effective technology for processing ores containing less than 0.5% copper. Before being leached with an acidic solution containing bacteria, the ore is first crushed and then heaped. These microorganisms catalyze the dissolution of copper. The resultant rich solution is extracted using solvent extraction and electrowinning (SX/EW). There are ongoing advancements in this technology, particularly with respect to the global processing factories that employ this method. The Escondida Mine in Chile, which processes ore containing 0.3-0.7% copper and produces 200,000 tons of copper cathode yearly, is one such facility (Watling, 2006).

### 6.2. Bioheap leaching

Bioheap leaching is a commercially proven technique for extracting low-grade refractory gold and secondary sulfide copper ores. The process involves reducing the ore to less than 19 mm in size and agglomerating it before acidifying it to provide a pH range favourable to bacterial growth. The conditioned ore is then placed on a pad, and the optimal microbial activity within the heap is dependent on the configuration of the irrigation and aeration systems. The temperature gradient within the reactor generates a complex and diverse range of microbial species within the heap.

Bioheap processing for refractory gold resembles that for copper in that bacteria oxidize sulfide minerals such as pyrite and arsenopyrite to liberate the fine gold particles trapped within them. The bioheap method can utilize ores with a sulfur concentration in the form of $S^{2-}$ ranging between 1% and 2.5%. In 1999, Newmont Mining Corporation developed this method to treat refractory sulfide gold ores with grades ranging from 1-3 g/t.

### 6.3. Stirred tank bioleaching

Despite its higher capital and operating costs compared to other biohydrometallurgical approaches, stirred tank technology is usually employed for concentrate processing. The tanks are equipped with an agitator to ensure an even distribution of oxygen and carbon dioxide in the slurry and to keep the solid concentrate suspended in the solution. The impeller is equipped with a blower to inject air into the slurry. In addition, the tank walls are fitted with a water cooling system because the oxidation of sulfide minerals is exothermic. The slurry temperature must be kept within a specified range according to the microbial living temperature. The residence time of the slurry in the stirred tank is between 4 and 6 days, depending on the sulfide concentration of the concentrate.

### 6.4. In-situ bioleaching

In-situ leaching does not necessitate the excavation and transportation of ore from the deposit (Bosecker, 1997; Liu and Brady, 1999). Through drilled holes, the leach solution is pumped into the ore deposit. The solution reacts with the mineral and dissolves the valuable metal, which is then further processed. In Canada, uranium is usually extracted via in-situ mining. Uranium ore ($UO_2$) is transformed into soluble uranyl ions $(UO_2)^{2+}$. This oxidation process comprises the cycling of $Fe^{2+}$ to $Fe^{3+}$. Microorganisms convert $Fe^{2+}$ to $Fe^{3+}$, which serves as an oxidant for U(IV) to U(III) (VI). Bioleaching for uranium at the Denison Mine contributed 10-15% of the world's total uranium production in 1984 (McCready and Gould, 1990). This technology has also been used at the Gunpowder Mammoth Mine in Australia to process secondary copper ore (chalcopyrite and bornite).

## 7. Biohydrometallurgical applications

### 7.1. Biooxidation pretreatment of gold ores

In 1986, the Fairview mine in South Africa conducted the first commercial application of bio-oxidation to treat refractory sulfide gold concentrate, and it is still in use today. Compared to pressure oxidation and roasting, biooxidation offers many benefits. Compared to conventional pre-treatment techniques, bio-oxidation has reduced operational and capital expenses, making it viable to process lower-grade refractory gold ores (Whitlock, 1997). Moreover, bio-oxidation is more straightforward because the mineral oxidation process occurs at an air pressure and relatively lower temperature of 20 to 80 °C. In addition, the bio-oxidation process produces less $CO_2$ because the oxidation products of sulfide minerals such as elemental sulfur, sulfate, arsenic, and iron remain in the liquid phase and because the sulfur in the ore is converted to soluble sulfate instead of SOx and NOx during pre-treatment. Moreover, hazardous As(III) is changed by the biological oxidation of the concentrate into stable As(V), which precipitates as iron arsenate (van Niekerk, 2001).

The biooxidation of concentrate in a continuous stirred tank reactor (CSTR), heap biooxidation for low-grade refractory gold ores, and biooxidation employing coating techniques are some of the biooxidation technologies that have been developed (Schippers et al., 2013). In a recent biooxidation study conducted in Indonesia, mixotrophic bacteria enhanced the amount of gold extracted via cyanidation from 72% to 92% (Mubarok et al., 2017; Purnomo et al., 2019; Winarko et al., 2015). According to other research, particle size significantly impacts the bio-oxidation process, with small particles (less than 38 μm) destroying bacterial cell walls during agitation (Acevedo et al., 2004; Nemati et al., 2000; Winarko, 2016). However, according to previous studies, some bacteria can prevent the ore from preg-robbing, raising the gold extraction rate during cyanidation to 94.7% (Amankwah et al., 2005).

### 7.2. Copper bioleaching

Leaching processes accounted for 10-20% of the world's copper production in the early 21st century and have continued to expand (Schippers et al., 2013). In 2010, approximately 38% of copper leaching operations employed bioleaching technology (Edelstein, 2016). Copper bioleaching is utilized in Chile, Peru, Australia, the United States, China, Mexico, Russia, Canada, and Myanmar. Commercial bioleaching technologies for copper are used for heap leaching of secondary copper ores. Chalcopyrite processing, the primary copper ore, is still developing and on a pilot scale. The oxidation of copper sulfide minerals generates protons ($H^+$) that serve as leaching agents for copper oxide and sulfide minerals.

Bioleaching is still the subject of ongoing research investigating its basics, modelling, and microbiological aspects. Iron- and sulfur-oxidizing bacteria were used to extract copper from complex copper sulfide ores successfully (Chaerun et al., 2017; Chaerun et al., 2018). The extraction level of Cu reached 85 to 90 %. In another investigation, bioleaching with the bacterial strain SKC/SAA-2 yielded a 94% copper extraction level (Yushandiana, 2016). According to a study by Puspasari (2016) and Putra (2016), the mixotrophic bacterium strain SKC/SAA-2 can leach copper sulfide ores containing covellite, chalcocite, chalcopyrite, and bornite.

### 7.3. Nickel bioleaching

During the 1990s, the application of bioleaching technology for nickel ore processing was investigated. At the Talvivaara Mine in Finland, bioleaching for nickel is used commercially to extract nickel, zinc, and copper from polymetallic ore (Johnson, 2014). The bioleaching procedure applies to both sulfide and lateritic nickel ores. The sulfide nickel ore's bioleaching procedure is comparable to that of sulfide minerals. However, the bioleaching procedure for lateritic nickel ore is slightly different. Under anaerobic conditions, organic acid compounds such as oxalic acid, citric acid, and others are utilized to perform bioleaching for a lateritic nickel. These organic acids can be generated through fermentation by microbes. By fermenting agricultural waste, fungi such as *Aspergillus niger* can produce citric acid (Honda et al., 2011).

Many studies on the bioleaching of lateritic nickel have been conducted in Indonesia. According to Mubarok et al. (2012), citric acid effectively dissolves nickel from saprolite ore. Chaerun et al. (2017a) reported that nickel could be extracted from limonite and saprolite ore using organic acids generated by the fungus *Aspergillus niger*. Astuti et al. (2016) demonstrated in another investigation that citric acid could yield significant nickel extraction percentages and is selective for other metals. Using organic acids in nickel extraction provides many advantages, including environmental friendliness and more excellent nickel leaching selectivity (Astuti et al., 2016; Chaerun et al., 2017a).

## 8. Mechanism of mineral oxidation by microorganisms

Biohydrometallurgical technology has been successfully implemented in numerous countries endowed with abundant mineral resources and robust mining and metallurgical industries. Notable examples include the USA, Canada, Finland, Brazil, Australia, Chile, South Africa, China, and Spain. The USA, in particular, has been a trailblazer in the realm of biohydrometallurgy, with mining industries such as PT Newmont in Nevada employing biooxidation technology, a subset of biohydrometallurgical technology, as a pre-treatment for refractory gold ore before cyanide-based gold extraction. The USA remains actively engaged in research and operational programs in this field.

Regrettably, despite the advancements in biohydrometallurgical technology in the aforementioned countries, its development in Indonesia has been sluggish and is currently confined to laboratory-scale research conducted solely at the Bandung Institute of Technology (ITB) at the Department of Metallurgical Engineering, Faculty Mining and Petroleum Engineering (FTTM). This can be attributed to several factors, including the dearth of Indonesian human resources specializing in biohydrometallurgy and the limited interest among mining and metallurgy experts in bioprocesses, largely due to the perception of biological processes as being slow and fraught with implementation challenges. Furthermore, the absence of a biohydrometallurgy course in universities offering metallurgical engineering programs also contributes to the slow development of biohydrometallurgical technology in Indonesia. Essentially, biohydrometallurgical technology remains relatively unknown in Indonesia, and experts in the field of biohydrometallurgy are scarce, with the ITB Metallurgical Engineering being the only institution housing experts in this field.

The underdevelopment of biohydrometallurgical technology in Indonesia, despite the country's abundant mineral resources and status as the world's leading nickel mine producer, can be attributed to a lack of expertise and familiarity with biohydrometallurgy. This is primarily due to the discipline's relative obscurity within the country. The successful application of biohydrometallurgical technology is contingent upon the specific mineralogical characteristics of the target minerals. For instance, the extraction of nickel from limonite-type nickel laterite ore, a prevalent nickel mineral in Indonesia, can be achieved using the fungus *Aspergillus niger* (Astuti et al., 2011; Chaerun et al., 2017a; Mubarok et al., 2011; Mubarok et al., 2013; Mubarok et al., 2013a; Mubarok et al., 2015) or iron- and sulfur-oxidizing bacteria (with the addition of pyrite mineral as an energy source) (Alting and Chaerun, 2011; Chaerun et al., 2015; Mubarok et al., 2016). This higlights the intricate relationship between the choice of microbes and the mineralogical properties of the ore in the biohydrometallurgical process. Consequently, researchers aiming to advance the field of biohydrometallurgy must possess proficiency in mineralogy, metallurgy, and microbiology, with a particular emphasis on Earth microbiology for chemolithotrophic/chemolithoautotrophic or mixotrophic prokaryotes, as opposed to chemorganotrophic/heterotrophic prokaryotes.

From a bioprocess technology perspective, the implementation of biohydrometallurgical technology in Indonesia faces several challenges. One significant obstacle is the extended duration of the bioprocess, which employs microbes, compared to conventional chemical processes that utilize inorganic or organic acids as leaching agents. This extended timeframe not only impedes the technology's development in Indonesia but also has economic implications, affecting the capital and operational costs of metallurgical or mining industries. Consequently, this could impact the profitability of these industries. Furthermore, the initial cost of implementing biohydrometallurgical technology is higher than that of traditional hydrometallurgical technology due to the need for additional infrastructure for microbial seeding and cultivation. This additional expense could deter investment in biohydrometallurgical technology. Lastly, the economic viability of biohydrometallurgical processes is subject to the fluctuating market prices of the extracted metals.

Nevertheless, the constraints and challenges encountered in the application of biohydrometallurgical technology can be mitigated through the following strategies:

a. Economically, the implementation of biohydrometallurgical technology in Indonesia can be facilitated by utilizing locally available materials or by recycling waste from metallurgical or other industries to secure the most cost-effective source of microbial nutrients. Potential waste sources for microbial nutrients include molasses from sugar factories, Palm Oil Mill Effluent (POME) from palm oil factories, and agricultural waste such as corn or cassava. Additionally, nutrients for iron- and sulfur-oxidizing bacteria can be sourced from pyrite, a gangue mineral from sulfide mineral mining/metallurgical industries, or from fine coal, a waste product from coal mining. By capitalizing on these waste materials, the cost of implementing biohydrometallurgical technology can be significantly reduced.
b. Given the longer duration of the bioprocess compared to chemical processes, it is crucial to optimize the bioprocess at both laboratory and pilot scales. This optimization aims to determine the most effective biohydrometallurgical parameters that yield the highest extraction performance, thereby maximizing the percentage of target metal extraction. This optimization is particularly important as the type of microbes used will vary depending on the type of mineral from which the target metal is to be extracted. By identifying the optimal

parameters for the biohydrometallurgical process, the duration of the process can be significantly reduced.

Moreover, the advancement of biohydrometallurgical technology in Indonesia is currently confined to laboratory-scale research. This includes investigations into metal extraction from sulfide minerals, oxide minerals, gold tailings, ferronickel slag, steel slag, coal fly ash, coal bottom ash, and Lapindo mud. Additionally, biohydrometallurgical processes such as biooxidation and bioleaching have been explored for the removal of ash and pyritic sulfur, as well as organic sulfur content from coal. The biooxidation process has also been employed as a pre-treatment for refractory gold sulfide ores to dissolve impurities associated with gold before the gold extraction process using cyanide. Furthermore, biohydrometallurgical technology research has been expanded to include phytomining, a process that utilizes plants for the extraction of nickel from low-grade limonite nickel ores and gold from refractory low-grade gold ores. A summary of these laboratory-scale studies is provided in Table 1.

**Table 1.** A summary of the laboratory-scale biohydrometallurgical studies in Indonesia

| Ore/Mineral | Metals extracted | Microbes/plants employed | Biohydrometallurgy process | Reference |
|---|---|---|---|---|
| Laterite ores (limonite & saprolite) | Ni | Mixotrophic bacteria, fungi | Direct bioleaching, Semi-direct bioleaching, indirect bioleaching | Chaerun et al. (2017a) |
| Complex copper sulfide ore | Cu | Mixotrophic bacteria | Direct bioleaching, Semi-direct bioleaching | Chaerun et al. (2017)<br>Chaerun et al. (2018) |
| Coal | Organic and inorganic sulfur removal | Mixotrophic bacteria | Biooxidation and bioleaching | Handayani et al. (2017)<br>Nurhawaisyah et al. (2019)<br>Nurhawaisyah et al. (2019a)<br>Arifin et al. (2020) |
| Tailings | Au, Ag | Mixotrophic bacteria | Biooxidation | Purnomo et al. (2019) |
| Refractory gold ores | Au, Ag | Mixotrophic bacteria | Biooxidation | Winarko et al. (2015)<br>Winarko (2016)<br>Mubarok et al. (2017)<br>Mubarok et al. (2021) |
| Galena concentrate: $PbS$ (38.26 wt.%) $ZnS$ (5.22 wt.%) $CuFeS_2$ (5.55 wt.%) | Pb, Zn, Cu | An iron- and sulfur-oxidizing mixotrophic bacterium (*Citrobacter* sp.) | Direct bioleaching, Semi-direct bioleaching | Chaerun et al. (2020b) |
| Ferronickel slag | Mg | Mixotrophic bacteria | Direct bioleaching, Semi-direct bioleaching | Chaerun et al. (2022) |
| Complex Pb-Zn ores | Pb, Zn | Mixotrophic bacteria | Direct bioleaching, Semi-direct bioleaching | Ongoing |
| Ferronickel slag | Si | Mixotrophic bacteria | Direct bioleaching, Semi-direct bioleaching | Ongoing |
| Waste rocks and Clays | Au, Ag | Mixotrophic bacteria | Biooxidation | Ongoing |
| Fly ash and fine coal | P, K, Si | Mixotrophic bacteria, fungi | Direct bioleaching | Ongoing |
| Fly ash and bottom ash | Rare earth elements (REEs) | Mixotrophic bacteria | Direct bioleaching, Semi-direct bioleaching | Ongoing |
| Steel slags | Ca | Mixotrophic bacteria, fungi | Direct bioleaching, Semi-direct bioleaching | Ongoing |
| Red mud | REEs | Mixotrophic bacteria, fungi | Direct bioleaching, Semi-direct bioleaching | Ongoing |
| Lapindo mud | REEs, Li, Sr | Mixotrophic bacteria | Direct bioleaching, Semi-direct bioleaching | Ongoing |
| Refractory gold ores | Au | *Piper betle*, *Cymbopogon citratus*, and *Chrysopogon zizanioides* | Phytomining | Ongoing |
| Limonite ores | Ni, Co, Cr | *Piper betle*, *Cymbopogon citratus*, and *Chrysopogon zizanioides* | Phytomining | Ongoing |

The technology of biohydrometallurgy holds significant potential for application within the mining and metallurgy industries in Indonesia, particularly those focused on sulfide minerals and coals. Coal industries across the nation could employ biohydrometallurgy to reduce sulfur contents, specifically organic sulfur content (Arifin et al., 2020; Handayani et al., 2017; Nurhawaisyah et al., 2019; Nurhawaisyah et al., 2019a). Additionally, mining and metallurgy enterprises working with sulfide minerals in Indonesia, such as PT. J Resources, The Wetar Copper Mine, PT Freeport Indonesia, PT Amman Mineral Nusa Tenggara, PT Bumi Suksesindo (BSI), and PT ANTAM Tbk, could also benefit from the integration of biohydrometallurgy technology.

## 9. Conclusion

The adoption of biohydrometallurgical technology into the mineral processing industry in Indonesia has the potential to yield significant gains. This innovative approach has already shown impressive results in the commercial processing of refractory copper, uranium, and gold ores, and bioleaching strategies for other metals are the subject of the continuing investigation. Since the activity and impact of microorganisms on the extraction of valuable metals from ores are primarily determined by the unique characteristics and mineralogy of each deposit, additional research must be conducted to develop tailored bioleaching and biooxidation strategies for the Indonesian context. Indonesia can improve its mining industry while reducing its environmental impact, paving the road for a more sustainable future by exploring the potential of these cutting-edge technologies.

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## Conflict of interest

The authors declare there is no conflict of interest in this study.

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