Journal of Geomine (2023), 1(4), 150-158
DOI: 10.22077/jgm.2024.7398.1023

A Review on the Heap Bioleaching of Copper from Low-Grade Fine Tailings

Mehdi Karimi[1], Seyyed Mohammad Raouf Hosseini[1], Ebrahim Azimi[1]

Recived: 2024 Mar. 08, Revised: 2024 May 31, Online Published: 2024 Jun. 15

ABSTRACT

In this review, the general mechanism of the Heap bioleaching process, the types of microorganisms involved in the process and the suitable conditions for the activity of each of the microorganisms, the parameters affecting the process, the advantages and disadvantages and the main problems and limitations of the heap bioleaching process are discussed. Considering the constant decrease in the grade of ore extracted from mines and the considerable amount of low-grade tailings deposited in processing plants and on the mine site, the use of traditional methods of hydrometallurgy and pyrometallurgy to recover valuable elements has no technical and economic justification. On the other hand, global demand for precious metals is increasing daily, but precious resources are dwindling. Therefore, the effort to achieve a cost-effective method is undeniable. Bioleaching using microorganisms to dissolve and recover valuable materials from the mentioned low-grade sources is a suitable and significant method due to the advantages of low investment, low required human resources and a simple process and to some extent without environmental complications. However, it can be said that the main problem of using microorganisms is the slow kinetics and the long process time to achieve the desired result.

KEYWORDS

Heap bioleaching, Low-grade ores, Fine tailings, Microorganism, Copper sulfide

I. INTRODUCTION

Sulfide tailings from mines and processing plants usually contain large amounts of valuable and dangerous metals that can be used as a valuable secondary raw material and a source of many metals with the possibility of industrial extraction (Opara, Blannin et al., 2022; Ristović et al., 2022). These tailings contain unstable oxide and sulfide minerals that, in the presence of biogeochemical substances (water, oxygen, various microorganisms), show a high reaction potential for the formation of acid mine drainage containing heavy metal ions, which causes pollution of surface and underground water and soil (Lorenzo-Tallafigo et al., 2022, Ristović et al., 2022).

Heap bioleaching and in-situ bioleaching processes are very important in directly extracting metals from sources such as deep abandoned mines and low-grade deposits. The first industrial-scale heap bioleaching for commercial purposes was introduced in 1958 at the Bingham Canyon copper mine (Utah, USA) to recover copper from low-grade deposits. From the 1980s onwards, a large number of copper bioleaching plants were set up in many countries around the world, and by 2000, global bioleaching copper production accounted for 25% of the world's copper production (Karaulova and Baizhigitov, 2024).

Zandukili et al. (2005) compared the bioleaching behavior of old and fresh flotation tailings of Sarcheshme copper complex with grades of 0.22% and 0.18%, respectively. After seven days of operation, the best extraction results were 64% and 68% of total copper in tank tests for old and fresh tailings. The results of the final tests in the columns showed that without inoculation with fresh and old tailings, copper recovery was obtained at 47% and 39% in 80 days, respectively, while with the inoculation of bacteria in the columns, copper extraction was obtained at the rate of 72% and 62% during the same leaching time.

Lotfian et al. (2012) investigated the bioleaching of low-grade chalcopyrite ore (1% chalcopyrite and 3% pyrite) using moderate thermophilic bacteria. Experiments using column reactors and investigating the effect of particle size (-12.7, -19.07, and -25.04 mm) and external addition of 10% (V/V) CO_2 to induced air Done. The results showed that copper recovery increased by reducing the particle size (-12.07 mm) and adding CO_2, and finally, 68.69% of copper was extracted.

Gang et al. (Zou, 2013) used columns with a diameter of 100 mm and a height of 1 m to investigate the performance of copper bioleaching in different conditions in the Zijinshan Heap Bioleaching Industrial Plant. At a temperature of 30ºC, 5 g/L of total iron, pH = 1.5, and without aeration, copper extraction reached

---

[1] Department of Mining Engineering, Isfahan University of Technology, Isfahan 8415683111, Iran
✉ S.M.R. Hosseini: r.hosseini@iut.ac.ir

80% and 85% after 90 and 200 days, respectively, which indicates the suitability of using bioleaching.

Menafi et al. (2013) investigated the possibility of using bioleaching to dissolve copper from sulphide porphyry ore obtained from a part of Sarcheshme copper complex. The ore sample contained 18% pyrite and 0.8% copper as secondary chalcocite and copper oxides. For column bioleaching experiments, ore samples (40 kg each; 12-75 mm) were used, which led to about 90% copper recovery, which was a 40% recovery increase compared to the abiotic control, so The test results were favorable for using the bioleaching method for this copper mineral.

Wang et al. (2016) used biohydrometallurgical technology to extract copper from ore at the Chambishi mine in Zambia. 93.29% copper extraction for small-scale column bioleaching was achieved within 63 days and 89.05% copper extraction for large-scale column bioleaching was achieved in 90 days, which confirms the suitability of the ores for effective extraction by bioleaching. Microorganisms were grown in a 6-stage large-scale culture in a sulfuric acid pond to be used in heap leaching, and copper extraction of about 50% was achieved within two months.

The amount of copper consumption in 2021 reached 25.26 million tons with an increase of 1% compared to 2020 (Yin et al., 2021). The demand for copper is increasing and the supply of high grade copper resources and easy extraction is decreasing (Chen et al., 2024). To meet the increasing demand for copper, much research have been conducted on low-grade copper ores, such as chalcopyrite and chalcocite, which account for about 80% of the world's copper reserves (Toro et al., 2021; Hesami et al., 2022; Chen et al., 2024).

The share of bioleaching in the production of copper in the United States is more than 15%. Copper recovery from low-grade deposits (containing 0.1%-0.3% metal) by bioleaching is 2 to 5 times more economical than conventional processing methods such as pyrometallurgy and hydrometallurgy (Karaulova and Baizhigitov, 2024). Bioleaching has been used in Kazakhstan, Uzbekistan, Armenia and Russia, usually for uranium, gold, copper and nickel and is currently being developed. (Karaulova and Baizhigitov, 2024). Extensive research and experiments on copper bioleaching are being carried out and its practical implementation was in the development and implementation stage. Considering the resources of countries with a high share of global production of minerals, addressing the issue of industrial tailings and low-grade ores is very important (Karaulova and Baizhigitov, 2024). Additionally, the cost of commercial products obtained from industrial tailings is 5 to 15 times cheaper than the products obtained from conventional deposits (Karaulova and Baizhigitov, 2024). Therefore, this method can be considered a win-win process because the main environmental risks can be reduced with the controlled oxidation of sulfides and at the same time, metals can be recovered and a part of the global demand for precious metals can be satisfied (Lorenzo-Tallafigo et al., 2022; Opara et al., 2022; Štyriaková et al., 2022; Zhang and Schippers, 2022). Bioleaching, which has advantages such as low investment, simple operation, and environmental-friendliness compared to traditional smelting, has been widely used to extract copper from low-grade copper sulfide ores (Toro et al., 2021; Hesami et al., 2022; Zhang and Schippers, 2022; Chen et al., 2024; Huo et al., 2024). However, one of the problems of using bioleaching can be pointed out as long running time and low efficiency (Chen et al., 2024). Biotechnology has been considered one of the emerging industries, and heap bioleaching is considered an ideal method for the processing of low-grade resistant sulfide ores (Li et al., 2021).

II. MECHANISM OF BIOLEACHING

Metal recovery from mineral sources is generally a chemical process and dissolution reactions are carried out with the help of Fe^{3+} and H^+. Bioleaching is also a chemical process and depends on the action of acidophilic microorganisms such as *Acidothiobacillus thiooxidan* and *Acidothiobacillus ferrooxidan*. The task of microorganisms is to produce the necessary chemicals (reagents such as Fe^{3+} and H^+) for leaching metal sulfides and providing space for reactions (by producing a layer of extracellular polymeric substances). Microorganisms convert metal sulfides into water-soluble metal sulfates using biochemical oxidation reactions (Kour et al., 2021). According to the conducted research, it has been concluded that the dissolution of all metal sulfides is not the same, and now the presentation of "thiosulfate" and "polysulfide" paths is the most complete explanation for the dissolution process of different metal sulfides (Panda et al., 2015).

(a) Thiosulfate pathway: This pathway is for acid-insoluble metal sulfides such as molybdenite (MoS_2), pyrite (FeS_2) and tungstenite (WS_2) and is shown in Fig. 1. The main role of microorganisms in this pathway is the recovery of Fe^{2+} from the oxidation of Fe^{3+}. Microorganisms such as *Thiobacillus ferrooxidan* are attached to the ore in cracks, corners, edges and defects through extracellular polymer materials. The general reactions for this pathway can be summarized in Eq.s (1) and (2) (Bruynesteyn, 1989; Panda et al., 2015; Srichandan, Mohapatra et al., 2020).

$$2MeS + Fe^{3+} + 3H_2O \rightarrow 2Me^{2+} + Fe^{2+} + S_2O^{2-}_3 + 6H^+ \qquad (1)$$

$$S_2O^{2-}_3 + 8Fe^{3+} + 5H_2O \rightarrow SO^{2-}_4 + 8Fe^{2+} + 10H^+$$
$$\Delta H = 19.825\ \text{Kcal} \qquad (2)$$

(b) Polysulfide pathway: This pathway is the dissolution mechanism of some acid-soluble metal sulfides such as arsenopyrite (FeAsS), galena (PbS), howrite (MnS_2), sphalerite (ZnS), and chalcopyrite ($CuFeS_2$) and is shown in Fig. 1. The dissolution of these metal sulfides by H^+ is by breaking the metal-sulfur bonds at low pH where the sulfur part is oxidized to elemental sulfur through polysulfides. The general reactions of the path can be summarized in Eq.s (3), (4), and (5), respectively (Bruynesteyn, 1989; Panda et al., 2015).

$$MeS + Fe^{3+} + H^+ \rightarrow Me^{2+} + Fe^{2+} + 0.5H_2S_n \ (n \geq 2) \tag{3}$$

$$0.5H_2S_n + Fe^{3+} \rightarrow 0.125S_8 + Fe^{2+} + H^+ \tag{4}$$

$$0.125S_8 + 1.5O^2 + H_2O \rightarrow SO^{2-}_4 + 2H^+, \Delta H=18.64 \text{ Kcal} \tag{5}$$

The mentioned pathways for the dissolution of metal sulfides are summarized in Fig. 1.

III. GENERAL PROCESS

The heap bioleaching process starts with the extraction of ore from the mine. It continues with crushing, agglomeration or pelletizing (if needed), heap construction, bioleaching, recovery of metals from the solution, regeneration of the leach solution and ends with tailings management. Fig. 2 shows the typical steps and processes of heap bioleaching. After the ore is crushed and piled on an impermeable liner to prevent the acid solution from penetrating the soil, the microbial solution is sprayed from the top of the heap. It penetrates downwards, dissolving the metal minerals through molecular permeation, microbial adsorption, and catalytic oxidation. By creating a slope of about 1 to 3% below the heap, the solution is collected and directed to a specific tank. The desired metal is recovered from the solution and after microbial regeneration, the solution is resprayed on the heap. Then, the metals in the solution or residue are recovered by the subsequent metal recovery process (Li et al., 2021).

IV. COMMON MICROORGANISMS INVOLVED IN THE BIOLEACHING PROCESS.

Several microorganisms that can biodissolve the metals in question from low-grade mineral resources and wastes of various industries are categorized based on their activity temperature and the description of each of them is discussed.

A. *Mesophilic microorganisms*

The suitable temperature for the growth and multiplication of these microbes is between 25-45ºC and most of them are active in pH between 1.5-3.5. This series of microbes can convert sulfur to acid and are entirely self-sufficient in terms of food. They can decompose carbon dioxide in the air and consume carbon and oxygen for their growth. Among the most critical mesophilic microbes, *Thiobacillus ferrooxidans*, *Thiobacillus thiooxidans*, and *Leptosperlium ferooxidans* can be mentioned (Bosecker, 1997; Zandevakili et al., 2005; Panda et al., 2015).

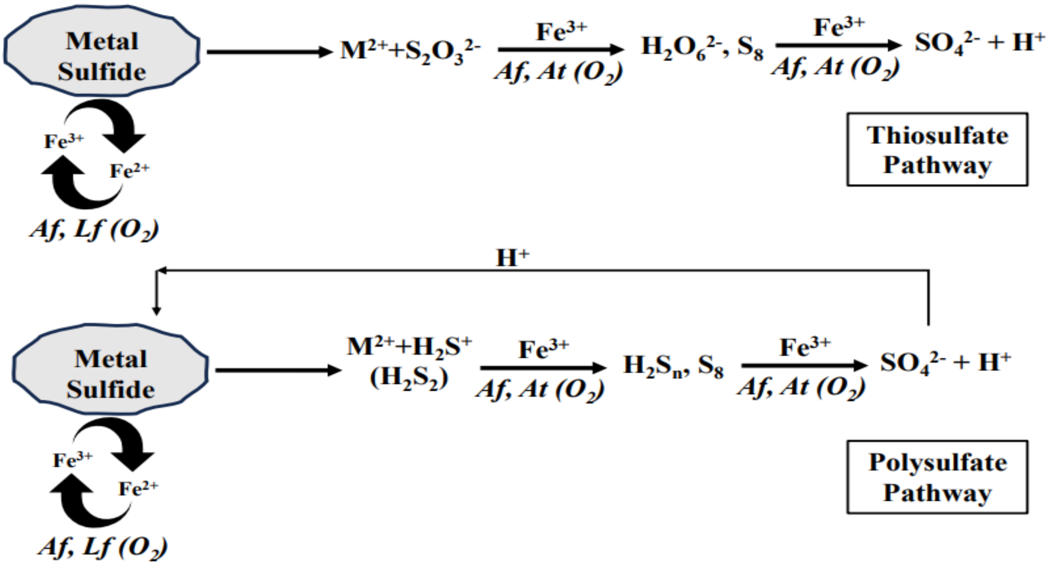

Fig. 1. Dissolving paths of metal sulfides a) thiosulfate path and b) polysulfide path (Bruynesteyn, 1989; Srichandan et al., 2020)

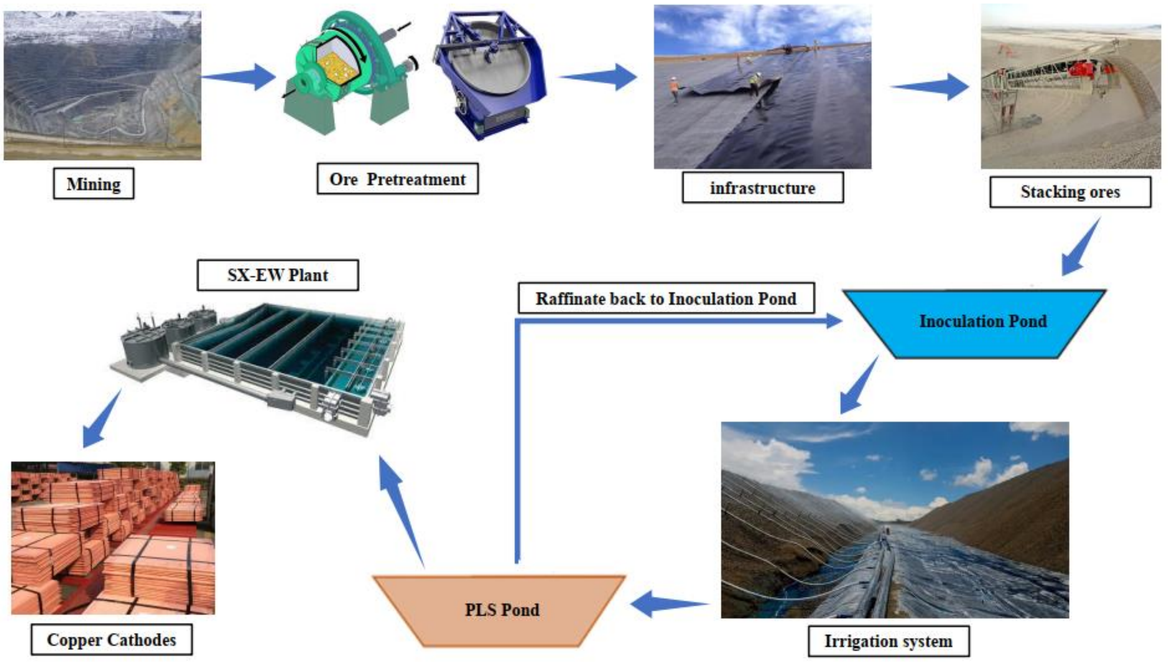

Fig. 2. Typical Heap bioleaching process cycle (Yin et al., 2018; Li et al., 2021)

B. *Moderate thermophilic microorganisms*

Like mesophiles, these microbes can oxidize pyrite, simple or mixed metal sulfides such as chalcopyrite. The suitable temperature for the growth of these microbes is between 40-60ºC and since heat accelerates chemical reactions, they are superior to mesophiles in terms of oxidation of mineral sulfurs. Because the oxidation of mineral sulfurs is exothermic and increases the environment's temperature. These microbes are not self-sufficient and nutrients must be provided in the environment for their growth (Zandevakili et al., 2005; Panda et al., 2015).

C. *Hyperthermophilic microorganisms*

These microbes are from *Sulfolobus* strain and are resistant to high temperatures up to 95ºC; therefore they are found in hot and acidic springs. These microbes can oxidize iron, mineral sulfur and mixed sulphide minerals such as chalcopyrite and convert sulfur to sulfuric acid in aerobic conditions and sulfur to H_2S in anaerobic conditions using ferric ions. These microbes are resistant in very acidic conditions even down to pH=0.5 and the oxidation rate of these microbes using ferric ions is much higher than moderate thermophilic microbes (Zandevakili et al., 2005; Panda et al. 2015).

V. ADVANTAGES OF HEAP BIOLEACHING OVER THE TRADITIONAL PROCESSES

A. *Low cost and simple equipment and setup*

Heap bioleaching is a simple process and does not require special equipment. Among the costs of this operation are labor and equipment such as pumps, pipes, and heap construction equipment. Due to the highly acidic environment, the equipment must be anti-corrosive (Li et al., 2021).

B. *Compatibility with the environment and no need for complex conditions*

Heap bioleaching does not require high temperatures or high pressure to dissolve minerals. The microbial solution can be recycled and the ore has sufficient particle size and strength, so the tailings can be stored on site or, after processing, sold as building or road material. Therefore, it reduces environmental pollution (Li et al., 2021).

C. *The possibility of using all mineral resources*

Considering the low cost of heap bioleaching, this process is suitable for the processing of low-grade ore and tailings. The processable grades of copper, gold and nickel ore are 0.1%, 0.5 ppm, and 0.2%, respectively (Li et al., 2021).

VI. PROBLEMS AND CHALLENGES OF HEAP BIOLEACHING

A. *The phenomenon of ineffectiveness* (*deactivation*)

Chalcopyrite is a primary copper sulfide with high activation energy. Impenetrable layers (S^0, S_n^{2-}, jarosite) are formed on the ore surface during bioleaching, thus preventing penetration and reducing the leaching rate (Li et al., 2021). This impenetrable layer can be removed by two methods:

(1) Control and reduction of the production of inactive layers that are directly or indirectly related to the control of temperature, pH, oxidation reduction potential (ORP), ion concentration and, or microbial community. The optimal temperature for chalcopyrite

bioleaching is between 60 and 80 °C, where there are few passive layers, which has led to the use of extreme thermophiles (Chen and Wen 2013; Yu et al., 2017, Ai et al., 2019). It has also been reported that adding 0.66 g/L sodium chloride can reduce the elemental sulfur content at the mineral level from 26% to 3% (Chang-Li, Jin-Lan et al., 2012).

(2) Removing inactive layers by physical and chemical methods such as adding a mixture of $NaCO_3$ + $(NH_4)_2CO_3$ + H_2O = 1:1:40 and then performing secondary leaching on the remaining minerals (Panda et al., 2013). Some microorganisms such as the heterotrophic bacterium Acidiphilium acidophilum can also destroy the impermeable layer (Zeng and Qiu, 2010). In addition, increasing pH and sulfate improves the stability of passive layers (Tshilombo, 2006).

B. *The concentration of ions in the solution*

The presence of a suitable concentration of some metal ions changes the electrochemical behavior of minerals and accelerates their dissolution. However, mineral dissolution can cause excessive ion concentrations in solution, many of which cannot be removed in the subsequent metal recovery process. They may inhibit microbial activity, increase solution density and viscosity, and affect the recovery of valuable metals. In addition, some ions with high concentrations are toxic to microorganisms (Li et al., 2021). In industrial scale and actual production, pulp needs regular purification. Under normal temperature and low pH conditions, 99.9% of iron can be removed through jarosite biogenesis in a bioleaching system (Li et al., 2021).

C. *Heap adjustment*

For an ore containing a certain amount of sulfide, the temperature is proportional to the square of the heap height. Although it is difficult to regulate the temperature in the heap, the temperature distribution can be controlled by adjusting the gas-liquid exchange and the height of the heap. For a high-height heap (>15 m), high liquid flow rates can be used to remove heat from the heap. For low heaps, the opposite is true (Rawlings and Johnson, 2007; Li et al., 2021). Research has shown that low watering and proper aeration rates are beneficial for maintaining heat in the mound. Also, heap height, irrigation rate, acid concentration and dropper spacing are the main design parameters that affect the metal leaching effect and their best values are presented (Dixon, 2000; Petersen and Dixon, 2007; Petersen, 2010).

D. *Aeration*

Both microbial growth and leaching reactions require O_2 or CO_2 and the consumption of these two gases are closely related. Sufficient oxygen obtained by natural air convection requires sufficient permeability in the heap. Generally, O_2 (>2 ppm) should be supplied by placing aeration tubes at the bottom of the heap. The carbon source in bioleaching is generally CO_2, which can be used by some autotrophic microorganisms. Except for the CO_2 produced by the decomposition of carbonates, most of the CO_2 comes from the air, but its content in the air is very low, and it is difficult to enter a higher heap. CO_2 plays the same important role as O_2. Therefore, it seems necessary to supplement CO_2 at the bottom of the heap (Li et al., 2021). The required amount of aeration can be calculated by the stoichiometric theory method. However, the total O_2 aerated by the bioleaching process is not used on an industrial scale, and the overall O_2 utilization efficiency of 20% was chosen for fan and pipe measurements (Logan et al., 2007). Researchers (Hatzikioseyian and Tsezos, 2006) evaluated the stoichiometry of microbial growth based on the bioenergetic reaction proposed by McCarty (McCarty, 1975). They concluded that 127 mg of O_2 and 21.8 mg of CO_2 to oxidize 1 g of iron, 1502 mg grams of O_2 and 685 mg of CO_2 are required to oxidize 1 g of sulfur. These data were applied in industrial heap bioleaching operations (Li et al., 2020). This enables us to determine the intensity of aeration required for heap bioleaching based on preliminary laboratory tests.

E. *Climatic preferences and environmental protection*

Generally, heap leaching is done outdoors, so factors such as sunlight, rain, temperature, altitude and wind affect heap structure, ORP, pH, microorganisms and reaction rate. Sunlight not only directly affects the temperature of the heap, but also accelerates the evaporation of water from the surface of the heap. Heavy rain can slow down the heap bioleaching process for several days, reducing metal production and lengthening the production period. Therefore, to prevent such incidents, a flood control pool with a volume of 3 to 5 times the tank should be installed. Some companies have attempted to cover the entire heap with a plastic membrane to reduce rainwater collection (Rawlings, 1997; Li et al., 2021). For arid regions, increased water consumption increases production costs. For cold regions, low temperatures reduce microbial activity (Li et al., 2021). These problems can be solved by corresponding measures such as installing a semi-buried drip irrigation system and covering the heap surface with a plastic membrane (Riekkola-Vanhanen, 2007; Riekkola-Vanhanen, 2013). In summary, areas with low rainfall, humid climate and high average temperature are suitable and optimal for heap bioleaching. Many technical measures such as semi-buried pipes, preheating the bacterial liquid, low aeration, and covering the heap surface with a membrane have been implemented to solve the mentioned problems (Li et al., 2021). A composite sublayer should prevent leakage and protect underground water and soil resources (Tuovinen et al., 2018).

Table 1 summarizes the general advantages and disadvantages of using the heap bioleaching process.

VII. FACTORS AFFECTING BIOLEACHING

A. *Microbial compatibility*

The ore may contain one or more metals that may have toxic effects on microorganisms. Therefore, the use of compatible microorganisms is a prerequisite in the bioleaching of ore and solid waste to enable living cells to resist the toxic effect of the concentration in the ore. Usually, acclimatization is done in low toxic metal concentration with increasing exposure to the dominant concentration in the ore (Bosecker, 1997).

B. *Nutrients*

Microorganisms involved in metal extraction from sulphide ores only need mineral compounds for growth such as nitrogen (N), potassium (K), phosphorus (P), and magnesium (Mg). In general, mineral nutrients are obtained from the environment and the materials that are going to be leached. For optimal growth, iron and sulfur compounds can be supplemented with ammonium, phosphate and magnesium salts (Bosecker, 1997).

C. *Oxygen and carbon dioxide*

Bioleaching is achieved in aerobic conditions, because the microorganisms involved are aerobic and need enough oxygen for their growth activity and to carry out their reactions. Sufficient oxygen supply is a prerequisite for good growth and high activity of microbes involved in the bioleaching process. In the laboratory, this can be achieved by aeration, stirring, or shaking. On an industrial scale, especially in the case of heap bioleaching, the supply of sufficient oxygen may cause problems. CO_2 is the source of carbon for the growth of bacteria and is supplied from the air. So, there is no need to add it from outside. Higher concentrations of CO_2 can lead to inhibitory effects (Bosecker, 1997). Dissolved oxygen affects the bio-oxidation and oxidation of Fe^{2+} to Fe^{3+} (Kour et al., 2021). Oxygen is used by cells as the final electron acceptor of their active metabolic pathway (Gentina and Acevedo, 2013).

D. *pH and ORP*

Adjusting the correct pH value is a necessary condition for the growth of microbes and is a determining factor for the dissolution of metals. pH for bioleaching by acidophiles is usually 1.5-2.5. A pH lower than one and higher than three may negatively affect microbial activity and ultimately reduce bioleaching performance (Srichandan et al., 2020). The pH changes during the bioleaching operation mainly due to microbial activity, i.e., oxidation of ferrous iron and sulfur compounds. The first one helps to increase pH while the second one helps to decrease it (Gentina and Acevedo, 2013).

ORP is a physicochemical state that changes during bioleaching due to cell activity. During copper extraction, the ORP level strongly depends on the ratio of ferric to ferrous ions, as well as other galvanic interactions. Usually, at the beginning of the bioleaching operation, the ORP of the leaching solution is about 350 mV, and the copper extraction rate becomes essential when the ORP values reach more than 450 mV. In this sense, ORP is a crucial variable to quantify during bioleaching in order to use it as an indicator to evaluate process behavior (Gentina and Acevedo, 2013).

Table 1. Advantages and disadvantages of heap bioleaching process (Ghorbani et al., 2011; Panda et al., 2012)

Disadvantages of heap (bio) leaching	Advantages of heap (bio) leaching
Long-term pilot programs	The best option for the processing of low-grade ore, tailings and small wastes
Slower metal recovery - long leaching and stoppage cycles	Feasibility of counterflow operation due to lack of liquid-solid separation stage
Larger surface area	Environmentally friendly (reducing severe environmental regulatory concerns)
Relatively lower recovery than milling/flotation or milling/leaching processes	No grinding step (may require crushing and stacking before heap loading)
Release of PLS to the environment	Low-cost technology (low operating and capital costs)
	Faster boot time
	The possibility of improving the metal grade when recycling the bacterial solution on the heaps
	Simplicity in equipment design and operation
	Simplicity of leaching operation in normal weather conditions

E. Temperature

Temperature is an important parameter that determines the type of microorganisms involved in the bioleaching process. Bacterial diversity and dominance during bioleaching also depend on temperature. The optimal temperature for the oxidation of ferrous iron and sulfide by *Thiobacillus ferrooxidan* is 28-30ºC. At lower temperatures, reduced metal extraction occurs, but even at 4°C, bacterial dissolution of copper, cobalt, nickel, and zinc has been observed. At higher temperatures (50-80ºC), thermophilic bacteria can be used for leaching (Bosecker, 1997). Sulfide oxidation rate and microbial activity increase with temperature. However, the temperature cannot be raised above the optimum for microbial growth. Beyond the optimal temperature, the microbial activity and bioleaching kinetics decreases. In this sense, thermophilic and hyperthermophilic microorganisms are preferred because they can withstand the highest operating temperatures that favor the chemical steps of copper dissolution. During bioleaching, there are several heat flows cause changes in system temperature, the main ones being those bacterial activity and from the chemical oxidation of reduced sulfur minerals. It is difficult to control these temperature changes, especially in static operation mode (in-situ leaching, dump and heap leaching), where comprehensive temperature profiles are created inside the ore beds, which affect the performance of the bioleaching operation in an inhomogeneous way (Gentina and Acevedo, 2013).

F. Spraying rate

To maximize the recovery performance, an optimal spraying rate of the solution containing the microbes is essential. A lower spray rate leads to a longer total column bioleaching time, while a higher rate can risk heat loss from the column, resulting in less ore dissolution (Mousavi et al., 2006).

In summary, further extraction of copper from low-grade tailings is controlled by a number of factors/parameters, including microbial factors, which are listed in Table 2.

VIII. AGGLOMERATION PROCESS

Due to the infiltration problems caused by soft clay deposits, they have caused problems in several heap leaching operations. Poor penetration can lead to low metal extraction due to solution channeling or creating impermeable (dead) areas within the heap. Improper heaping is one of the main causes of permeability problems. To overcome permeability problems, significant progress was made by introducing agglomeration before ore stacking. If the ore particles and, or agglomerates are of similar size, segregation can be largely avoided. Agglomeration improves the uniform penetration of the solution through the ore heap and can be used for many ores, residues, and ground tailings (Dhawan et al., 2013). According to industrial data, permeability in agglomerated heaps can be improved by 10-100 times, leaching time can be reduced by 0.5-0.33 times, acid consumption can be reduced by 20-30%, and the copper extraction rate can be increased by 10 to 30 percent (Wang et al., 2021). To better maintain the stability of the created agglomerates, adhesives are used, which are divided into organic, inorganic and polymeric adhesives (Lewandowski and Kawatra, 2009).

There are different methods to achieve agglomeration in industrial heap leaching. The best methods include the use of drums, discs, and conveyors, which are briefly described below (Lewandowski and Kawatra, 2009).

A. Agglomeration by drum

It is one of the most common types of agglomeration with the possibility of high-power application. For drum agglomeration, rotation speed, rotation angle, drum size (length-to-diameter ratio), and agglomeration time are usually defined as important parameters (Lewandowski and Kawatra, 2009; Wang et al., 2021). The slope of the drum is usually between 1 and 4 degrees from the horizon, the time that the ore remains in the drum is between 1 (for coarse ore with few fine grains) and 4 min (for ore with high moisture), the rotation speed is 20-60% of the critical speed and the ratio of the length to the diameter of the drum is between 2.5-5. In general, agglomerates are usually kept in the drum for approximately 1 to 5 min (Lewandowski and Kawatra, 2009; Wang et al., 2021).

B. Agglomeration by disc

Due to the lower operational power, it is mostly used in laboratory environments. This method is proper when working with fine materials and can usually produce agglomerates of uniform size with excellent raw strength. The inclination of the disk is usually between 40 and 65 degrees from the horizon, the revolutions per minute of the disk, depending on the diameter and inclination of the disk may vary from 30 to 50 degrees, the disks usually operate at 50 to 75% of their critical speed, depending on the size of the ore particles, and the diameter of the disk. The depth of the disk can be from 0.46 to 0.91 m. Disc agglomerators can be found with a diameter of about 300 mm for laboratory-scale processes and up to 10 m in diameter for production units. Larger disks can process approximately 110 t/h (Lewandowski and Kawatra, 2009; Wang et al., 2021).

Table 2. Factors and parameters affecting mineral oxidation and metal dissolution in the heap bioleaching process (Pradhan et al., 2008; Ghorbani et al., 2011; Panda et al. 2012)

Processing/Conditions	Mineral properties	Biological parameters	Physical and chemical parameters
Pulp density	Mineral type	Microbial activities	Temperature
Heap geometry	Acid consumption	Population density	pH
Practical weather conditions	Penetration of minerals	Microbial diversity	ORP
Circulation of bacterial solution	Particle size	Spatial distribution of microorganisms	Water potential
Rest periods	Area	Binding to ore particles	O_2 content and availability
Flow rate of the bacterial solution to the heap	porosity	Metal tolerance	CO_2 content
	Hydrophobic	Microbial adaptability	Mass transfer
	Galvanic interactions		Nutrient availability
	Formation of secondary minerals		Fe^{3+} concentration
			Light
			Pressure
			Surface tension
			The presence of inhibitors

C. *Conveyor agglomeration*

It is one of the most common agglomeration methods due to its low cost. This method works best with a low amount of fine particles. They usually work at a speed between 76-91 m/min and often at an angle of 15°. If 15% of the material is smaller than 150 µm, it is suggested that the material should be agglomerated on a disc or in a drum. Water can be sprayed onto the material during discharge onto the conveyor at transfer points or along the belt. It is often common to add a final moisture spray at the end of the conveyor to aid in agglomeration, which may occur as agglomerates move into the heap or depot area. In general, agglomerates have a residence time of approximately 10 to 15 sec (Lewandowski and Kawatra, 2009; Wang et al., 2021).

IX. CONCLUSION

The grade of mineral resources is constantly decreasing due to continuous extraction, while the amount of low-grade resources deposited, such as tailings from mines and tailings from processing plants, is increasing daily. On the other hand, the usual methods of processing and concentrating these resources are technically and economically impossible due to the lower grade than acceptable in the usual methods. Therefore, obtaining a low-cost and environmentally friendly method for extracting valuable elements from these low-grade resources is essential and undeniable. Heap bioleaching can be a suitable method for extracting valuable metals such as gold, silver, copper and uranium from low grade sources on an industrial scale. In this study, all aspects of the heap bioleaching operation, such as the mechanism and general method of operation, the most important microorganisms involved in the process, the advantages of this method over other methods and common problems in the implementation of the process, the factors affecting the process and the agglomeration operation were discussed. Also, several research and laboratory and industrial performances of the past were reviewed. According to the results of this research, it can be said that heap bioleaching is an effective and helpful method and usually has a high recovery percentage for processing low-grade resources and wastes. Among the advantages of this method, we can mention lower cost, more compatibility with the environment, less required human resources and more straightforward design and implementation. In contrast the low efficiency factor and long implementation time are the main disadvantages of this method.

ACKNOWLEDGMENT

The authors would like to acknowledge the Iran National Science Foundation (INSF) for supporting this research under the grant number of 99021932, and the Mining Engineering Department of the Isfahan University of Technology for granting access to the infrastructures.

REFERENCES

Ai, C., Z. Yan, H. Chai, T. Gu, J. Wang, L. Chai, G. Qiu and Zeng, W. (2019). "Increased chalcopyrite bioleaching capabilities of extremely thermoacidophilic Metallosphaera sedula inocula by mixotrophic propagation." Journal of Industrial Microbiology and Biotechnology 46(8): 1113-1127.

Bosecker, K. (1997). Bioleaching: metal solubilization by microorganisms. FEMS Microbiology reviews 20(3-4): 591-604.

Bruynesteyn, A. (1989). "Mineral biotechnology." Journal of Biotechnology 11(1): 1-10.

Chang-Li, L., X. Jin-Lan, N. Zhen-Yuan, Y. Yi and Chen-Yan M. (2012). Effect of sodium chloride on sulfur speciation of chalcopyrite bioleached by the extreme thermophile Acidianus manzaensis. Bioresource Technology 110: 462-467.

Chen, B.-W. and Wen J.K. (2013). Feasibility study on heap bioleaching of chalcopyrite. Rare Metals 32: 524-531.

Chen, W., H. Tang, S. Yin, L. Wang and Zhang, M. (2024). Copper recovery from low-grade copper sulfides using bioleaching and its community structure succession in the presence of Sargassum. Journal of Environmental Management 349: 119549.

Dhawan, N., M. S. Safarzadeh, J. D. Miller, M. S. Moats and Rajamani, R.K. (2013). Crushed ore agglomeration and its control for heap leach operations. Minerals Engineering 41: 53-70.

Dixon, D. G. (2000). Analysis of heat conservation during copper sulphide heap leaching. Hydrometallurgy 58(1): 27-41.

Gentina, J. C. and F. Acevedo (2013). Application of bioleaching to copper mining in Chile. Electronic Journal of Biotechnology 16(3): 16-16.

Ghorbani, Y., M. Becker, A. Mainza, Franzidis, J.P. and Petersen, J. (2011). Large particle effects in chemical/biochemical heap leach processes–a review. Minerals Engineering 24(11): 1172-1184.

Hatzikioseyian, A. and Tsezos, M. (2006). Modelling of microbial metabolism stoichiometry: application in bioleaching processes. Hydrometallurgy, 83(1-4): 29-34.

Hesami, R., A. Ahmadi, M. R. Hosseini and Manafi, Z. (2022). Electroleaching kinetics of molybdenite concentrate of Sarcheshmeh copper complex in chloride media. Minerals Engineering 186: 107721.

Huo, X., Liu, J., Hong, X., Bai, H., Chen, Z., Che, L., Yang, Y., Tong Y., and Feng, S. (2024). Enhancing column bioleaching of chalcocite by isolated iron metabolism partners Leptospirillum ferriphilum/Acidiphilium sp. coupling with systematically utilizing cellulosic waste. Bioresource Technology 394: 130193.

Karaulova, Z. and D. Baizhigitov (2024). Bioleaching for Efficient Copper Ore Recovery. International Journal of Chemical and Molecular Engineering 18(2): 29-36.

Kour, G., R. Kothari, H. Mohan Singh, D. Pathania and S. Dhar (2021). Microbial leaching for valuable metals harvesting: versatility for the bioeconomy. Environmental Sustainability 4(2): 215-229.

Lewandowski, K. and S. K. Kawatra (2009). Binders for heap leaching agglomeration. Mining, Metallurgy & Exploration 26(1): 1-24.

Li, J., L. Tong, Y. Xia, H. Yang, W. Sand, H. Xie, B. Lan, S. Zhong and A. Auwalu (2020). Microbial synergy and stoichiometry in heap biooxidation of low-grade porphyry arsenic-bearing gold ore. Extremophiles 24: 355-364.

Li, J., H. Yang, L. Tong and W. Sand (2021). Some Aspects of Industrial Heap Bioleaching Technology: From Basics to Practice. Mineral Processing and Extractive Metallurgy Review: 1-19.

Logan, T. C., T. Seal and J. A. Brierley (2007). Whole-ore heap biooxidation of sulfidic gold-bearing ores. Biomining, Springer: 113-138.

Lorenzo-Tallafigo, J., N. Iglesias-González, A. Romero-García, A. Mazuelos, P. R. del Amo, R. Romero and F. Carranza (2022). The reprocessing of hydrometallurgical sulphidic tailings by bioleaching: the extraction of metals and the use of biogenic liquors. Minerals Engineering 176: 107343.

Lotfalian, M., M. Schaffie, E. Darezereshki, Z. Manafi and M. Ranjbar (2012). Column bioleaching of low-grade chalcopyritic ore using moderate thermophile bacteria. Geomicrobiology Journal 29(8): 697-703.

Manafi, Z., H. Abdollahi and O. H. Tuovinen (2013). Shake flask and column bioleaching of a pyritic porphyry copper sulphide ore. International Journal of Mineral Processing 119: 16-20.

McCarty, P. L. (1975). Stoichiometry of biological reactions.

Mousavi, S., A. Jafari, S. Yaghmaei, M. Vossoughi and R. Roostaazad (2006). Bioleaching of low-grade sphalerite using a column reactor. Hydrometallurgy 82(1-2): 75-82.

Opara, C. B., R. Blannin, D. Ebert, M. Frenzel, K. Pollmann and S. Kutschke (2022). Bioleaching of metal (loid) s from sulfidic mine tailings and waste rock from the Neves Corvo mine, Portugal, by an acidophilic consortium. Minerals Engineering 188: 107831.

Panda, S., A. Akcil, N. Pradhan and H. Deveci (2015). Current scenario of chalcopyrite bioleaching: A review on the recent advances to its heap-leach technology. Bioresource technology 196: 694-706.

Panda, S., P. Parhi, B. Nayak, N. Pradhan, U. Mohapatra and L. Sukla (2013). Two step meso-acidophilic bioleaching of chalcopyrite containing ball mill spillage and removal of the surface passivation layer. Bioresource technology 130: 332-338.

Panda, S., K. Sanjay, L. Sukla, N. Pradhan, T. Subbaiah, B. Mishra, M. Prasad and S. Ray (2012). Insights into heap bioleaching of low grade chalcopyrite ores—A pilot scale study. Hydrometallurgy 125: 157-165.

Petersen, J. (2010). Modelling of bioleach processes: connection between science and engineering. Hydrometallurgy 104(3-4): 404-409.

Petersen, J. and D. Dixon (2007). Modelling zinc heap bioleaching. Hydrometallurgy 85(2-4): 127-143.

Pradhan, N., K. Nathsarma, K. S. Rao, L. Sukla and B. Mishra (2008). Heap bioleaching of chalcopyrite: a review. Minerals Engineering 21(5): 355-365.

Rawlings, D. E. (1997). Mesophilic, autotrophic bioleaching bacteria: description, physiology and role. Biomining: theory, microbes and industrial processes, Springer: 229-245.

Rawlings, D. E. and D. B. Johnson (2007). Biomining, Springer.

Riekkola-Vanhanen, M. (2007). Talvivaara black schist bioheapleaching demonstration plant. Advanced Materials Research 20: 30-33.

Riekkola-Vanhanen, M. (2013). Talvivaara mining company–From a project to a mine. Minerals Engineering 48: 2-9.

Ristović, I., D. Štyriaková, I. Štyriaková, J. Šuba and E. Širadović (2022). Bioleaching process for copper extraction from waste in alkaline and acid medium. Minerals 12(1): 100.

Srichandan, H., R. K. Mohapatra, P. K. Singh, S. Mishra, P. K. Parhi and K. Naik (2020). Column bioleaching applications, process development, mechanism, parametric effect and modelling: A review. Journal of Industrial and Engineering Chemistry 90: 1-16.

Toro, N., Y. Ghorbani, M. D. Turan, P. Robles and E. Gálvez (2021). Gangues and clays minerals as rate-limiting factors in copper heap leaching: A review. Metals 11(10): 1539.

Tshilombo, A. F. (2006). Mechanism and kinetics of chalcopyrite passivation and depassivation during ferric and microbial leaching, University of British Columbia.

Tuovinen, H., M. Pelkonen, J. Lempinen, E. Pohjolainen, D. Read, D. Solatie and J. Lehto (2018). Behaviour of metals during bioheap leaching at the talvivaara mine, Finland. Geosciences 8(2): 66.

Wang, J., H. Zhao, W. Qin, X. Liu and G. Qiu (2016). Industrial practice of biohydrometallurgy in Zambia. Rare Metal Technology 2015: 3-10.

Wang, L., S. Yin and A. Wu (2021). Ore agglomeration behavior and its key controlling factors in heap leaching of low-grade copper minerals. Journal of Cleaner Production 279: 123705.

Yin, S.-h., W. Chen, X.-l. Fan, J.-m. Liu and L.-b. Wu (2021). Review and prospects of bioleaching in the Chinese mining industry. International Journal of Minerals, Metallurgy and Materials 28: 1397-1412.

Yin, S., L. Wang, E. Kabwe, X. Chen, R. Yan, K. An, L. Zhang and A. Wu (2018). Copper bioleaching in China: Review and prospect. Minerals 8(2): 32.

Yu, R. L., A. Liu, Y. Liu, Z. Yu, T. Peng, X. Wu, L. Shen, Y. Liu, J. Li and X. Liu (2017). Evolution of Sulfobacillus thermosulfidooxidans secreting alginate during bioleaching of chalcopyrite concentrate. Journal of applied microbiology 122(6): 1586-1594.

Zandevakili, S., M. Ranjbar and Z. Manafi (2005). Investigation of bioleaching efficiency for copper recovery from flotation tailing of Sarcheshmeh copper mine. Iranian Mining Engineering Conference, Shahid Bahonar University of Kerman.

Zeng, W. and G. Qiu (2010). Development of heap bioleaching of copper sulphide ores. Jinshu Kuangshan/Metal Mine(8).

Zhang, R. and A. Schippers (2022). Stirred-tank bioleaching of copper and cobalt from mine tailings in Chile. Minerals Engineering 180: 107514.

Zou, G., Z. L. Wu, X. K. Lai, L. C. Zou, R. M. Ruan, S. Papirio and J. Puhakka (2013). Column bioleaching of low grade copper sulfide ore at extreme conditions for most mineral processing bacteria. Advanced Materials Research, Trans Tech Publ.