

Bioleaching Process for the Recovery of Metals: A Review

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Abstract

Bioleaching is a modest and operative technology for extracting metals from low-grade ores and mineral distillates, based on the metabolic action of microbes. In sulfide reserves, chemolithotrophic bacteria such as *Thiobacillus thiooxidans* and *Thiobacillus ferrooxidans* oxidize

insoluble metal sulfides into soluble metal sulfates, allowing metal recovery, while heterotrophic bacteria and fungi that solubilize metals through the production of

organic acid-treated non-sulfide ores. Presently, bioleaching is useful mostly for the recovery of copper, uranium, and gold, with heap, dump, and in-situ leaching being the principal industrial techniques, while stirred-tank bioleaching is used for dealing refractory gold ores. In addition to mineral extraction, bioleaching also holds important potential for metal retrieval and detoxification of industrial wastes, sewage sludge, and heavy-metal-contaminated soils.

Introduction

Waste containing organic compounds and heavy metals in the environment increases with the development of technology in industries which is a severe threat for human health and the environment (Islam et al., 2021). Heavy metals usually arsenic is toxic even at very low concentration and the contamination caused by these metals is a threat for environment and public health. Recovery of these heavy metals and some of the precious metals like gold, silver and platinum from solid waste and the earth's crust is a critical issue now a days (Pathak et al., 2022). There are two conventional methods for the recovery of these metals as hydrometallurgy and pyrometallurgy. Environmentally harmful chemicals are used in hydrometallurgy for metal leaching and multiple byproducts while pyrometallurgy uses thermal methods for the recovery of metals from solid waste, high energy consumption and dangerous gases involved in thermal techniques that are hazardous for the environment (Naseri et al., 2022). This environmental toxicity causes multiple human diseases including neurological and psychological disorders, organ disorders, behavioral disorders, immunodeficiencies and various forms of cancers.

Environment friendly biotechnological techniques as the use of microorganisms to reduce the toxicity of these waste products provides highly efficient results and cost

effective. Method used for the extraction of metals from mines and ores was bioleaching in nineteenth century. Which is used for the recovery of metals with low cost, low energy consumption, high efficiency and eco-friendly way. Bioleaching is used as alternative method to conventional methods for the extraction of metals (Hosseinzadeh et al., 2021). Various types of microorganisms used such as heterotrophic and autotrophic bacteria, and fungi for the extraction of metal ions from the solid waste and transfer them into a solution. Microorganisms removed metals from the solid waste by using two methods, direct and in-direct bioleaching. Microbes produce metabolites for the removal of metals without contacting solid waste in indirect technique while microorganisms participate directly into the process and solubilize the metals by electrochemical reaction. Autotrophic bacteria depend on organic carbon for carbon source as an alternative atmospheric carbon fixation involved in their growth (Hoque & Philip, 2011). For the recovery of metals from industrial wastes and e-waste by gram-negative bacteria which grow aerobically such as Sulphur oxidizing bacteria (SOB) and iron oxidizing bacteria (IOB) are prominent for the recovery of metals (Biswal et al., 2018).

Types of Microorganisms used in Bioleaching

1. *Thermophilic Bacteria*

The bacteria grow on moderate temperature of 50°C and on pyrite, chalcopyrite and pentlandite are called *thiobacillus* like bacteria. These bacteria grow on yeast extract and ferrous iron is used as energy source. Extremely thermophilic bacteria were isolated by Brierley and his co-workers which can grow on temperature above 60°C. Some of the facultative aerobes, chemolithoautotrophic bacteria, *Acidians* Brierley, associated with genus *sulfolobus* while elemental sulphur, metal sulphides and ferrous iron used for the growth of extremely acidophilic *Archaeon*. Elemental sulphur is used as electron acceptor

and reduced to H_2S under anaerobic conditions. *Sulphobacillus thermosulphidooxidans* facultative autotrophic and spore forming bacteria also used ferrous iron, sulphides and elemental sulfur as energy source and grow in the presence of yeast extract.

2. *Thiobacillus*

Gram-negative, aerobic, spore forming, rod shaped bacteria belong to the genus *thiobacillus* most active in the process of bioleaching. These *thiobacillus* bacteria used carbon dioxide from the atmosphere as a source of carbon for the growth of new cells and oxidation of reduced sulfides, elemental sulfur and thiosulfate used as the source of energy. The acidophilic species *thiobacillus thiooxidans*, *thiobacillus ferrooxidans* are important because the bacterial bioleaching occurs in acidic environment of pH 1.5- 3 in which most of the metal ions remain in solution. Other *thiobacillus* bacteria can oxidize sulfur and sulfides but they grow on high pH in which metal ions do not maintain in solution.

Waksman and Joffe in 1922 isolated the *Thiobacillus thiooxidans* that involved in the rapid oxidation of elemental sulfur. Sulfuric acid is generated by other partially reduced sulfur compounds and decreased the pH of the medium from 1.5 to 1. Rocks rapidly decomposed by the use of sulfuric acid and the acid soluble metal ions can pass into a solution. Colmer and Hinkle in 1947 isolated most important bacteria for leaching, *thiobacillus ferrooxidans* from the acid coal mines. These bacteria used ferrous iron as electron acceptor and do not derive energy from oxidation of reduced sulfur while in the absence of oxygen these can grow on the reduced sulfur compounds and ferric ion used as electron acceptor (Leduc & Ferroni, 1994). A new group of metal mobilizing bacteria is *T. prosperus* which are halotolerant in nature. Some of the facultative

chemolithoautotrophic bacterium involved in the oxidation of metal sulfides is *T. cuprinus* which mobilize copper from chalcopyrite (Huber & Stetter, 1989).

3. *Leptospirillum*

It is another type of bacterium which tolerates high concentration of silver, molybdenum, uranium and low pH involved in the oxidation of ferrous iron while unable to oxidize sulfur isolated from mine waters in Armenia. *L. ferrooxidans*, *T. ferrooxidans* and *T. thiooxidans* are mesophilic bacteria that can grow on 25-35 temperature (Norris, 1989).

4. Heterotrophic Microorganisms

The process of metal leaching also occurs with the help of microorganisms (bacteria, fungi) which gain their energy from organic supplements. These microbes do not get any benefit with the process of metal leaching (Ehrlich, 1997). Highly oxidized metal compounds reduced by enzymes and involved in solubilization of enzymes as in case of manganese leaching. The microbes secrete hydrophilic reactive groups and organic acids in the medium and dissolve heavy metals. For the solubilization of metals, the bacterial genus *Bacillus* and fungal genera *Penicillium* and *Aspergillus* are most important ones (Bosecker, 1997).

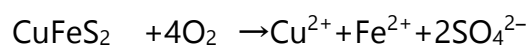
Mechanisms of Bioleaching

The conversion of insoluble metal minerals into soluble metal minerals or extraction of metals with the help of microorganisms. Bacterial metabolic enzymes involved in the oxidation-reduction reactions.

1. Direct Enzymatic Bioleaching

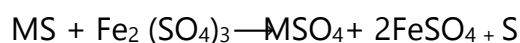
The process in which bacteria directly in physical contact with the surfaces of minerals in which electrons directly transfer from copper or sulfide in case of Cu_2S helped Fe to bound to the exopolymer and the cell envelope. Microbes attached and attacked only

once on the surface of the metal sulfide which is due to the bacterial cell division and the huge number of bacterial daughter cells. The direct enzymatic degradation involves



2. In-Direct Bioleaching

The chemical oxidation of sulfide minerals with the help of bacteria produces leach liquor. Ferric iron and solubilized metal exist in the leach liquor. The pH of the solution must be acidic for the oxidation of metal sulfides. In this process bacteria have no need to be in direct contact with the surface of mineral but it is a slow process as compare to direct presence of bacteria that re-oxidize the ferrous iron in a pH of 2-3.



These both methods, direct and in direct bioleaching, occur side by side naturally and technically because ferric iron keeps in oxidized state by the bacteria involved in sustaining the high redox potential.

Factors Effecting Bioleaching

The composition of ores and the efficiency of microorganisms effect the process of bioleaching. The optimum growth and the leaching conditions influence the yield of metal extraction.

1. Nutrients

Chemolithoautotrophic bacteria use in-organic compounds for their growth and these nutrients obtained from the leaching metals. Magnesium, ammonium and phosphate salts used as supplements with iron and sulfide compounds for the optimal growth of microbes (Zhang et al., 2011).

2. Temperature

It depends on the type of micro-organism involved in the process of bioleaching as each microbe has its own optimum temperature like *T. ferrooxidans* used the temperature between 28 C to 30 C for the oxidation of ferrous iron and sulfide. Thermophilic bacteria used high temperature for the purpose of bioleaching (50-80 C). It is also observed that at lower temperature bacterial solubilization of zinc, nickel, cobalt and copper also occur (Watling et al., 2017).

3. Mineral Substrates

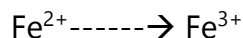
The chemistry, type and structure of the substrate effect the efficiency of bioleaching and determine the oxidation rate, microbial attachment and the metal recovery. Some of the minerals formed passive layers and slow kinetics like chalcopyrite (Watling, 2006). While in the presence of iron and sulfur oxidizers some mineral involved in rapid dissolution (Rawlings, 2005). The smooth and crystal structure of minerals lowers the leaching process while the rough and porous structure significantly improves the leaching rates (Hubau & Bryan, 2022).

4. Effect of pH

Microbial growth and activity strongly controlled by pH. Acidophilic microbes have high activity in low pH conditions like *acidithiobacillus* and *leptospirillum* have strong oxidation rates while solubility of many metals increases which improves the extraction ability of microbes. In common microbial strains pH ranges 1.5-2.0 for the best extraction of metals which become negligible near neutral pH. In less acidic conditions microbial activity and metal oxidation sharply reduced (Vera et al., 2013).

5. Oxygen and Carbon-Dioxide

Most of the micro-organisms used oxygen for the process of oxidation of metals as



if the concentration of oxygen becomes low the microbial activity and the oxidation of metals dissolution slow down. For chemo lithotrophic microbe carbon-dioxide required as a source of carbon which is fixed by Calvin cycle for the production of biomass. The optimal concentration of carbon-dioxide should be 1-5% which significantly increase the Fe^{2+} oxidation rate and improve the stability of acidic conditions that are required for the process of bioleaching (Bonnefoy & Holmes, 2012).

6. Surfactant and Organic Extractant

Microbial activity usually effected by the use of organic surfactants as they involved in the destruction of microbial cells and reduce the rate of oxidation. Low concentration (>5mg/L) of organic extractants may involve in the solubilization of metals. They have both positive and negative effects on the process of bioleaching as organic surfactant may increase the microbial attachment by increasing the mineral wettability and also improve the recovery of metals (Nikolić et al., 2014).

7. Heavy Metals

The type and concentration of heavy metals effects the process of leaching positively and negatively. Some metals like copper, zinc, iron, cobalt and nickel act as cofactors in the enzymatic activity of microbes, rate of oxidation and metal solubilization. By increasing the concentration of metals they may damage the microbial cells, reduce the oxidation rate, enzymatic activity and rate of metal solubilization (Rohwerder et al., 2003).

Bioleaching Techniques

The simple and effective technique for the processing of sulfide ores and extraction of copper and uranium is bioleaching which depends on the composition of ores and activity of micro-organisms. These techniques are specific for specific type of ores.

1. Column Leaching\Percolator Leaching Technique

This technique is used to study the extraction of metals by vertical column of glass or PVC for leachability under controlled conditions in which packed material of ore, waste material and soil is used for the continuous flow of leach solution. A column is packed with crushed material and microbial medium, acid and water applied from the top which dissolves metals and contaminants by percolating downwards. Chemical analysis of the collected effluents performed periodically. This technique is used for the study of long term leaching behavior of microbes and to design industrial heap leaching (Kossoff et al., 2014).

Classical and early column-based leaching in which liquid (water, acid or base) moves downward under gravity through a fixed bed of solid material is known as percolator leaching. It is applied for the process of diffusion-controlled leaching which is commonly used for the extraction of uranium and copper ores. Air lift percolators were used for the bacterial leaching process in which the sieve plate bottom part of glass tube percolator is filled with ore particles (Van der Sloot et al., 2003).

2. Sub-Merged Leaching

In the absence of oxygen, submerged leaching replaced the percolator leaching in which fine grained material that is suspended in the liquid and kept in stirring and motion. Control of parameters, higher rate of aeration and accurate monitoring helpful in the activity and growth of bacteria which reduces the reaction time and increases the extraction of metals. This process can be carried out in a bioreactor and suitable for the treatment of concentrated ores, bio-desulfurization of coal and industrial waste products (Ehrlich, 1997).

Heap Leaching

This is an industrial leaching process in which pipes are placed in strategic positions to provide oxygen to the deeper portion of the heap during the construction and used for the fine-grained ores that cannot be used for concentrated flotation. Large basins of up to 12000 tons of ores are used for heap leaching (Brierley, 2008).

Dump Leaching

It is the oldest technique of industrial process in which the size and amount of the ore range from several hundred thousand tons. Acidified water, acid ferric sulphate solution or water may be used as lixiviant, sprinkled or flooded continuously on the top of the dump. Then the leachate pass through an oxidation basin for the regeneration of the bacteria and ferric iron (Johnson, 2014).

Tank Leaching

It is the most effective technique for the treatment of ore concentrates and helpful in extracting more than 80% of the zinc from the zinc concentrates. The construction of bioreactor is more expensive than the other types of industrial processes but the rate of ore extraction is very high. Tank leaching is also used for the extraction of gold ores recently (Schipper et al., 2013).

Discussion

An alternative to conventional metal extraction techniques for low grades metals is bioleaching. Its key benefit lies in the application of naturally occurring microorganisms to solubilize metals below mild temperature and pressure conditions, resulting in lower energy utilization and reduced greenhouse gas releases. Studies have revealed that bioleaching is especially active for copper sulfides, refractory gold ores, zinc, nickel, cobalt, and uranium minerals (Johnson et al., 2021).

Instead of its advantages, bioleaching faces numerous technical and operational challenges. One of the primary restrictions is its **slow metal suspension kinetics**, mainly in heap and dump leaching systems. Minerals such as chalcopyrite show passivation layers that meaningfully reduce leaching efficacy (Panda et al., 2013). Moreover, microbial activity is extremely sensitive to environmental parameters such as pH, temperature, oxygen availability, and nutrient supply, making progression control difficult at industrial scale.

Another concern is the **generation of acidic sewages** and utilization of toxic elements, which may cause environmental risks if not appropriately managed. Although bioleaching is measured environmentally friendly compared to smelting, unsuitable containment and monitoring can result in acid mine drainage (AMD) and groundwater contamination (Akcil et al., 2007).

Economic possibility also a serious issue. While capital and operating expenses are generally lower than orthodox methods, bioleaching needs long residence times and large land areas for heap operations. Subsequently, its application is mainly restricted to low-grade ores that are uneconomical to process by conventional techniques (Brierley & Brierley, 2013).

Future Prospects

The future of bioleaching is auspicious due to rising demand for metals, deteriorating ore grades, and environmental protocols. Developments in **microbial biotechnology** are expected to meaningfully improve process efficacy. The use of genetically engineered or selectively modified microbial consortia proficient of tolerating high metal concentrations, risky acidity, and raised temperatures may overwhelmed current kinetic restrictions.

Bioleaching is also gaining consideration for the **retrieval of critical and strategic metals** such as lithium, cobalt, rare earth elements (REEs), and metals from industrial wastes. Biomining of waste materials suggests a workable solution for metal recovery while dropping environmental pollution.

Upcoming industrial implementation will likely involve **hybrid systems**, combining bioleaching with chemical leaching, flotation, or solvent extraction to expand overall metal retrieval and economic capability. Additionally, improved reactor design, real-time monitoring, and digital procedure control using artificial intelligence and modeling tools may convert bioleaching into a more expectable and effective technology.

Conclusion

In conclusion, bioleaching characterizes an important technology for sustainable metal extraction in the age of declining ore grades and environmental limitations. Although challenges associated with kinetics, process regulator, and ecological management persist, ongoing advancements in microbial ecosystem, reactor engineering, and waste valorization strongly support its expanded future application in both mining and reprocessing industries.

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