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Green mining: Advances in biomining technologies - A review

Durgapada Sarkhel
Department of Biotechnology, MITS School of Biotechnology, Bhubaneshwar, India

ABSTRACT

Biomining, a cutting-edge approach in mining, harnesses the metabolic capabilities of microorganisms to extract metals from ores and mine waste materials. This biotechnological method offers a sustainable alternative to conventional mining techniques by minimizing environmental impacts and improving resource recovery efficiency. The process involves two primary methods: bioleaching and bio-oxidation. Bioleaching employs acidophilic bacteria, such as *Acidithiobacillus ferrooxidans* and *Acidithiobacillus thiooxidans*, which thrive in acidic environments and oxidize sulfide minerals in ores to solubilize metals like copper, gold, and uranium. These bacteria catalyze the dissolution of metal sulfides, releasing metals into solution for subsequent extraction. Bio-oxidation, on the other hand, uses microorganisms like *Acidithiobacillus ferrooxidans* to oxidize refractory sulfide minerals that are not amenable to conventional extraction methods. This enhances the accessibility of metals like gold and arsenic, making them easier to recover through subsequent processes. The advantages of biomining extend beyond improved metal recovery rates. It reduces the need for energy-intensive processes such as smelting and grinding, thus lowering greenhouse gas emissions and operational costs. Additionally, biomining can remediate mine waste by detoxifying tailings and reducing their environmental impact. However, biomining faces challenges such as the optimization of microbial activity in large-scale operations and the management of microbial communities to prevent contamination. Research continues to explore novel microbial species and genetic engineering techniques to enhance biomining efficiency and broaden its applicability to diverse mineral types and environmental conditions. In conclusion, biomining represents a promising frontier in geobiotechnology, offering sustainable solutions to mineral extraction while addressing environmental concerns associated with traditional mining practices. Continued advancements in microbial ecology and bioprocess engineering will further unlock the potential of biomining in the global mining industry.

KEYWORDS

Biomining; Bioleaching; Bio-oxidation; Microorganisms; Sustainable mining

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Introduction

Humans have extracted metals from mineral ores, typically found as metal sulphides in nature, including copper, nickel, cobalt, lead, and zinc. These sulphides are insoluble under normal environmental conditions, necessitating enrichment processes like flotation to obtain concentrates. However, for low-sulphide ores where flotation is uneconomical, a sustainable and cost-effective alternative is bio-mining, a well-established biotechnology now globally adopted [1].

Bio-mining involves bio-leaching, where insoluble metallic compounds are biologically converted into soluble forms. This process primarily utilizes acidophilic aerobic bacteria or archaea such as *Acidithiobacillus ferrooxidans* and *Leptospirillum ferrooxidans* [2]. These microorganisms oxidize metal sulphides in acidic conditions, producing metal ions and sulphate. The oxidation process is facilitated by microbial iron (II) oxidation, generating Fe (III) as the oxidizing agent. Consequently, sulphur compounds and elemental sulphur are converted into sulphuric acid, creating an acidic environment conducive to leaching [3].

In industrial applications, bio-mining has revolutionized the extraction of metals from low-grade ores, particularly copper, which now constitutes a significant portion of global production. The method has also proven effective for extracting gold, cobalt, nickel, zinc, and uranium. Advancements in plant construction, heap leaching processes, and microbial understanding have propelled bio-mining to compete successfully with traditional hydro-metallurgical chemical processes. Challenges remain in managing the residues generated during bio-leaching, such as iron sulphates and dilute sulphuric acid, which require effective treatment and disposal methods [4].

Overall, bio-mining stands as an eco-friendly and economically viable alternative in modern mining practices, driven by technological innovations and growing expertise in microbial biogeotechnology [5].

Sulphide Ore

Porphyry deposits are the primary sources of global copper and molybdenum, also yielding gold, silver, tin, platinum, palladium, and tungsten. These deposits are typically associated with subduction zones and volcanic archipelagos, leading to significant deposits in regions such as the Andes, the Rocky Mountains, the Philippines, and Papua New Guinea [6]. Currently, 50-60% of global copper and 95% of molybdenum production originate from these deposits. Key ore minerals include copper iron sulfides like chalcopyrite

***Correspondence:** Mr. Durgapada Sarkhel, Department of Biotechnology, MITS School of Biotechnology, Bhubaneswar, India 11566, e-mail: Durgapadasarkhel98@gmail.com

($CuFeS_2$) and bornite (Cu_5FeS_4), as well as enargite (Cu_3AsS_4). Molybdenum, in the form of molybdenite (MoS_2), and gold are significant byproducts [7].

Near-surface areas experience supergene enrichment, characterized by simpler copper sulfides such as chalcocite-digenite (Cu2-xS) and covellite (CuS). Despite the low ore content (0.2-1.5 wt.% copper), the extensive volume of these deposits makes them highly profitable, although they produce large quantities of tailings prone to acid mine drainage [8].

Sediment-hosted polymetallic deposits are the second most crucial source of copper globally. Besides copper, these deposits yield key byproducts such as silver, cobalt, lead, and zinc. Notable examples include the Central African Copperbelt in Zambia and the Democratic Republic of the Congo, and the Permian copper shale deposits in Central Europe, particularly in Poland and Germany [9]. The primary minerals in these deposits are copper sulfides like chalcocite and copper-iron sulfides such as bornite (Cu5FeS4), with some chalcopyrite. These deposits also contain cobalt, zinc, and lead in sulfide form. The copper content in these deposits is generally 1-2 wt.%, with varying concentrations of associated byproducts [10].

Overall, these deposits, despite their low-grade ores, are economically viable due to their massive scale and valuable byproducts, necessitating careful management of environmental impacts like acid mine drainage.

Bio-Leaching and Bio-Oxidation

Bio-leaching utilizes microorganisms to transform ores containing insoluble valuable metals into a soluble form, facilitating the extraction of these metals. The process is particularly effective for extracting gold from refractory ores through bio-oxidation in large plant tanks, preparing the metal for subsequent processing steps [11].

Industrial bio-leaching of sulfide-containing ores involves three primary methods:

- Heap or dump bio-leaching of predominantly low-grade sulfide ores
- Stirred-tank bio-leaching, such as for copper concentrates
- In-situ (or in-place) bio-leaching, such as for uranium

Heap or dump leaching, particularly of secondary copper ores like chalcocite and covellite, is the most significant method for copper bio-leaching. Approximately 80% of bio-leached copper is derived from projects focusing on these secondary ores [12].

In-situ bio-leaching eliminates the need for traditional mining by extracting the ore directly within its natural deposit. This method has been demonstrated for copper and zinc extraction in countries such as Germany (Rammelsberg), Ireland, Italy, Romania, Australia, and South Africa, with uranium being industrially extracted in Canada and at the Wismut site in Königsstein. In each instance, ore blocks were separated underground and leached in place. In Bulgaria, direct in-situ leaching involved pressing the leaching liquid into the shale. To prevent environmental issues and losses, bottom sealing is essential during in-situ leaching in mines. Another challenge is to halt the leaching process post-mine closure [13].

Bio-oxidation processes can be categorized into three types:

- Dump leaching for low-grade, refractory gold ores
- Stirred-tank bio-leaching for refractory gold ores with higher gold content
- Covering inert tailings with sulfide-containing gold concentrates followed by leaching in ventilated tanks or ore heaps

Gold cannot be directly leached organically as it is already in the metallic state, unaffected by oxidation or reduction. However, bio-oxidation targets the iron and potentially arsenic sulfide matrix in which gold is embedded, either within the crystal lattice or as particles. By leaching out the oxidized mineral components, the previously inaccessible refractory gold becomes available for extraction [14].

Copper

Research from the Federal Institute for Geosciences and Natural Resources (BGR) indicates that at least 8% of the primary copper production in 2010, which totaled 15.7 million tonnes, was derived from bio-leaching of sulfurous copper ores [15]. This figure includes heap leaching processes to a minor extent, where low-grade sulfide ores undergo direct bio-leaching without additional crushing (run-of-mine) in processes such as dump bio-leaching in the United States. Due to the lack of specific production numbers for these processes, there remains an undetermined but significant proportion of biologically leached copper [16].

In heap bio-leaching, ores are stacked in heaps, and leaching solutions are percolated through the heap to dissolve the copper. This process benefits from the activity of microorganisms, which facilitate the oxidation and dissolution of the copper sulfides. The resulting copper-laden solution is collected and processed to recover the copper metal. The efficiency of bio-leaching in recovering copper from low-grade ores makes it an increasingly important method, particularly as high-grade ore reserves diminish [17].

Overall, the proportion of bio-mined copper compared to conventionally mined copper is estimated to exceed 10-20%. This method's growing significance highlights the potential of biotechnological approaches in the sustainable extraction of essential metals, reducing the environmental impact and enhancing the economic viability of mining operations [18].

Nickel, Cobalt and Zinc

Compared to copper, bioleaching for metals such as nickel, cobalt, and zinc is less common. An example is the Talvivaara project in Finland, where biological dump leaching is used to extract 50,000 tons of nickel, 90,000 tons of zinc, 15,000 tons of copper, and 1,800 tons of cobalt annually from low-grade ores. This process has the potential to contribute around 3% of the world's primary nickel supply [19].

Another example is the tank bioleaching plant in Kasese, Uganda, where 240 tons of pyrite concentrate are oxidized daily to extract cobalt, copper, nickel, and zinc. This facility produces approximately 1,100 tons of cobalt per year, accounting for about 1.25% of the global cobalt production, which was around 88,000 tons in 2010 [20].

These examples illustrate that while bioleaching is more established for copper, it has significant potential for other

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metals, albeit currently representing a smaller portion of their global production. The advancement of bioleaching techniques could enhance the extraction efficiency of these metals from low-grade ores, offering a more sustainable and economically viable alternative to traditional mining methods.

Uranium

In-situ bioleaching of uranium ore involves the oxidation of insoluble UO_2 directly within the deposit to water-soluble uranyl ions $[UO_2]^{2+}$ using microorganisms like *Acidithiobacillus ferrooxidans*. This process converts Uranium (IV) to Uranium(VI) while reducing Fe(III) to Fe(II) in a redox reaction. The Fe(III) required for oxidizing UO2 is regenerated through microbial oxidation of iron(II) [21].

Globally, around 30 active in-situ leaching projects for uranium contribute approximately 34,000 tons of uranium, representing about one-third of the global uranium production capacity. The efficiency of in-situ uranium leaching is high, with an estimated yield of 70-80%. However, environmental concerns arise due to the potential uncontrolled seepage of the leaching solution. Additionally, the presence of suitable substrates for leaching microorganisms, such as FeS2 and Fe(II), poses a long-term risk. Even decades after the cessation of active production, the leaching process may continue, threatening groundwater and surface water [22].

Up until 1990, Germany's Wismut company utilized biological methods to produce uranium through in-situ leaching at Königstein and heap leaching at Ronneburg. These methods involved the controlled use of microorganisms to extract uranium, demonstrating the feasibility and efficiency of bioleaching in uranium recovery.

While in-situ leaching presents a highly effective means of extracting uranium, it requires careful management to mitigate environmental risks. Long-term monitoring and containment strategies are essential to prevent contamination of water resources. The historical application of these methods in Germany highlights both the potential and the challenges of bioleaching in uranium mining [23].

Gold

According to the BGR, at least 16 active gold projects currently employ bio-oxidation, producing a minimum of 90 tonnes of gold and 161 tonnes of silver. This method accounts for approximately 3.5% of global gold production, which totaled around 2,450 tonnes in 2010. In comparison, 444 gold projects use hydrometallurgical processes, either as a primary or secondary method, with a combined gold production capacity of about 1,950 tonnes [24].

Bio-oxidation is a biotechnological approach that leverages naturally occurring bacteria to oxidize and break down the sulfide minerals surrounding gold particles, making the gold more accessible for extraction. This method is particularly advantageous for treating refractory gold ores, which are challenging to process using conventional methods due to the encapsulation of gold in sulfide minerals [25].

The utilization of bio-oxidation in gold mining has gained traction due to its environmental benefits and cost-effectiveness compared to traditional roasting and pressure oxidation techniques. The process reduces the need for high temperatures and pressures, minimizing energy consumption and greenhouse gas emissions. Additionally, bio-oxidation generates less toxic waste, contributing to a lower environmental impact [26].

The success of bio-oxidation projects is evident in their significant contribution to gold production, despite the relatively small number of active projects. These projects have demonstrated the potential to improve gold recovery rates from refractory ores, making previously uneconomic deposits viable for mining.

Hydrometallurgical processes, on the other hand, encompass a range of techniques including cyanidation, where gold is dissolved in a cyanide solution to separate it from the ore. These processes are widely used due to their efficiency and ability to handle large-scale operations. The substantial gold production capacity of hydrometallurgical projects underscores their importance in the gold mining industry [27].

Silicate, Carbonate and Oxide Ores

Industrial-scale biotechnical preparation of carbonate, silicate, and oxide-containing ores remains limited. In Slovakia, heterotrophic microorganisms are used to remove iron from kaolin, enhancing its quality. Other promising applications include the extraction of aluminum and lithium from spodumene ($LiAl[Si_2O_6]$), cobalt and nickel from laterites, and cobalt, nickel, copper, and manganese from polymetallic deep-sea nodules. Notably, significant nickel laterite deposits are found in subtropical and tropical regions, with deposits containing 2% nickel identified in the Saxon Granulite Mountains [28].

Laboratory studies have demonstrated the feasibility of bioleaching ores using heterotrophic bacteria and fungi. These microorganisms necessitate the addition of organic carbon sources, such as agricultural waste, food industry byproducts, or biomass e.g., algae. However, process control can be costly, and the presence of undesirable microorganisms may cause disruptions since sterile conditions cannot be maintained [29].

A novel approach, anaerobic bioleaching (Ferredox process), has been recently developed in the laboratory for processing carbonate, silicate, and oxide-containing ores. This method employs *Acidithiobacillus ferrooxidans* under anaerobic conditions to oxidize added sulfur, reducing Fe(III) and simultaneously solubilizing laterites [30].

This emerging technology holds significant potential for advancing the biotechnical preparation of various ores. However, its practical application at an industrial scale will require further research and development to optimize process efficiency and address associated challenges, including cost control and microbial contamination.

Future Prospectus and Challenges

The future of bio-mining holds promise as a sustainable and environmentally friendly approach to mineral extraction. Bio-mining, also known as biomining or bioleaching, utilizes microorganisms to extract metals from ores, offering several advantages over traditional mining methods [31]. These microorganisms, typically bacteria or fungi, catalyze chemical reactions that dissolve metals from minerals, making them accessible for recovery.

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One of the key benefits of bio-mining is its potential to reduce the environmental impact associated with conventional mining. Unlike traditional methods that involve large-scale excavation and chemical processing, bio-mining operates at ambient temperatures and pressures, minimizing energy consumption and greenhouse gas emissions [32]. Additionally, it can access metals from low-grade ores that are economically unfeasible with traditional mining techniques, thus extending the lifespan of existing mineral reserves.

Bio-mining also presents opportunities for resource recovery from waste materials, such as mine tailings and electronic waste, which contain valuable metals. By applying bioleaching techniques to these materials, bio-mining not only reduces waste but also recovers metals that can be reused in various industries [33].

However, several challenges hinder the widespread adoption of bio-mining on an industrial scale. One major challenge is the optimization of microbial processes to enhance metal recovery rates and efficiency. Microbial activity can be influenced by factors like pH, temperature, and nutrient availability, requiring careful control and monitoring in large-scale operations [34].

Another challenge is the management of microbial communities to prevent contamination and maintain process stability. Undesirable microorganisms or changes in environmental conditions can affect the efficiency and reliability of bio-mining operations, necessitating robust microbial management strategies [35].

Furthermore, the economic viability of bio-mining depends on factors such as metal prices, technological advancements, and regulatory frameworks. Investments in research and development are crucial to overcoming these challenges and unlocking the full potential of bio-mining as a sustainable solution for mineral extraction in the future.

Conclusions

In conclusion, current efforts in biotechnological mining focus on enhancing copper extraction from primary copper sulphides like chalcopyrites. Traditional heap bioleaching with mesophilic bacteria operates at moderate temperatures, but advancements seek to exploit thermophilic archaea (*genera Acidianus, Metallosphaera, Sulfolobus*) for bioleaching at around 65 °C. Both tank and heap bioleaching at higher temperatures are being piloted, necessitating careful material and process management.

Laboratory studies also explore electrochemically controlled tank bioleaching methods for chalcopyrites, showing potential for high copper yields. Industrially, bio-mining is currently restricted to sulphide and uranium ores, with ongoing research into biotechnological processes for silicate and oxide ore digestion, including the promising Ferredox process for laterites and oxide ores.

Future prospects include exploring anaerobic bioleaching possibilities, although specific microbial candidates with potential remain largely undiscovered and uncultured. The potential of bio-mining for recovering rare earths and metals used in electronics remains uncertain but holds promise as a cost-effective reprocessing treatment.

In summary, while bio-mining has made significant strides in enhancing copper extraction efficiency from sulphide ores, further research is needed to expand its application to other ore types and explore its full potential in recovering valuable metals critical for technological applications.

Disclosure statement

No potential conflict of interest was reported by the authors.

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