Nature's Chemist: Harnessing Microbes for Metal Recovery

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Abstract

Biomining, or bioleaching, is an eco-friendly and energy-efficient method that uses specialized bacteria to extract valuable metals like copper, gold, and uranium from low-grade ores and mining waste. These chemolithoautotrophic microbes, such as *Acidithiobacillus ferrooxidans, Acidobacillus thioxidans, Leptosprillum thioxidans* oxidize iron and sulphur compounds, thriving in acidic, mineral-rich environments. Their natural abilities make them ideal for sustainable ore processing, with minimal environmental impact compared to traditional smelting. Recent advances in genomics, molecular biology, and biofilm research have deepened our understanding of these microbes, though challenges remain in culturing and genetic manipulation. Industrial biomining is now widely practiced using heap and stirred-tank methods, and future innovations are focused on high-temperature processes using thermophilic archaea to enhance recovery from refractory ores.

Introduction

Microorganism, or simply microbes are living organism not visible through naked eye. They are incredibly diverse and play vital roles in various applications including food production, medicine, environmental management, fuel production and biotechnology. They are used in the production of fermented foods, beverages, fuel, biofertilizers, creation of vaccines and antibiotics, waste water treatment, bioremediation, development of various enzymes, chemicals and in biomining. The fascinating discovery of biomining has transformed our understanding of how nature can assist in solving some of humanity's most pressing industrial challenges. At the heart of this innovation lie tiny yet powerful organisms, bacteria. These microscopic miners have opened up a sustainable, low-cost, and Environment and Eco-friendly alternative to traditional methods of metal extraction. Rather than relying on energy intensive and polluting techniques such as smelting or chemical leaching, biomining harnesses the natural metabolic activities of specific microorganisms to extract valuable metals like copper, gold, uranium, and nickel from low-grade ores. This groundbreaking approach is not only revolutionizing the mining industry but also reducing ecological damage, preserving energy, and enabling metal recovery from waste and contaminated environments. As research progresses, the potential of biomining using bacteria continues to grow blending microbiology, biotechnology, and environmental engineering into a promising field of bio-based resource recovery.

Biomining or bioleaching

The term bioleaching refers to the conversion of insoluble metal (like metal sulphides) into a soluble form using acidiphilic, chemolithotropic iron and sulphur oxidising bacteria. The use of these bacterias to extract metals from ores is simply harnessing of a natural process of commercial purposes. Microbes have participated in the deposition and solubilisation of heavy metals in the Earth's crust since geologically ancient times. This ability of some microorganism particularly bacteria to solubilise metal from ores has given rise to microbial mining industry (1).

The use of microorganism in ore processing has several merits over traditional physico-chemical methods. Almost without any exception, microbial biomining is environmentally friendly and doesn't cause any type of potential hazard to environment. They do not require the high amount of energy used during roasting and smelting and do not produce sulphur dioxide or other harmful gaseous emissions or volatile compounds. Furthermore, mine tail and wastes produced from physico-chemical process when exposed to rain and air may be biologically leached, producing unwanted acids and metal pollution. Biomining also has a clear advantage in the extraction of low-grade metal ores. For example, Copper can be recovered from low grade ores and dumps left behind from previous mining operations by using biological activity that takes place during controlled irrigation at the dump (2). Many of these metals are not economically recoverable by physico-chemical methods.

General characteristics of biomining microbes

The primary biomining microbes have some common physiological features. They are all chemolithotropic and are able to utilize ferrous ion and reduced inorganic sulphur or both as electron donors. They can fix carbondioxide although there is considerable variations in the efficiency with which this is done. The less efficient carbondioxide fixing bacterial species require either elevated level of carbondioxide or a small amount of yeast extracts to rapidly grow. Biomining bacteria are generally resistant to a range of metal ions. These common properties explain why biomining organism are ideally suited to growing in the inorganic environment created by the active aeration of a substance suitable iron or sulphur containing mineral in water. Air ensures the carbon source in the form of carbondioxide and the preferred electron acceptor in the form of dioxygen and mineral ore provides electron donor (ferrous iron or/and reduced sulphur) and water is the medium for growth. Some biomining organism can also fix nitrogen from air.

Isolation and detection of biomining microbes

Microbial diversity in biomining is rapidly growing and increasing screening of diverse minerals and new detection techniques are revealing a wide variety of microbes with biomining potential. There are challenges in culturing acidophilic chemolithoautotrophs. These microbes are extremely sensitive to organic contaminants in gelling agents like agar, making them hard to grow on conventional solid media(3).Improvised Media Techniques like double-layer plate method is effective using heterotrophs in a base layer to absorb impurities, allowing chemolithoautotrophs to grow on a clean inorganic top layer(4,5).Many Biomining bacteria grow in biofilms., these bacteria often form biofilms on mineral surfaces or within rock pores, making isolation and lab cultivation difficult. Microbes used in lab experiments often fail to reflect survival and competitiveness of organisms in real,non-sterile biomining operation. Despite advances, certain key organisms may never be grown in lab media due to their highly specific environmental dependencies. Polymerase Chain Reaction (PCR) of 16S rRNA genes enables identification of microbial DNA directly from environmental samples, bypassing the need for cultivation but some microbes don't lyse easily, and DNA from solid samples can be hard to extract, which may bias detection toward only certain microbes (6). Thanks to PCR, we can now analyze microbial communities in stirred reactors and leaching heaps even if they don't grow in lab condition.

Genomics of microbes in biomining

The most intensively studied organism in biomining is *Acidithiobacillus ferrooxidans,* especially the ATCC23270 strain. This microbe's genome, around 2.7 million base pairs long, has been sequenced by major research groups, providing a deep insight into its biology(7,8). Scientists have successfully cloned many of its genes into E. coli, allowing controlled laboratory studies (9). Advanced genetic tools, such as gene replacement and transformation methods (e.g., conjugation and electroporation), have enabled researchers to manipulate these bacteria, although technical difficulties persist. Despite the potential, commercial application of genetically modified biomining microbes remains limited. Challenges include difficulties in culturing and engineering these microbes, and public concerns regarding GMOs. Moreover, because biomining typically occurs in non-sterile environments like mines and heaps, genetically modified strains would require strict containment protocols something current processing systems do not easily allow. Other biomining microbes like At. Thiooxidans and *Leptospirillum* have been less studied, with only a few genes cloned. However, recent genomic breakthroughs have shed light on extremophiles such as *Thermoplasma* and *Sulfolobus*, organisms that may thrive in high-temperature mining environments. With ongoing research, these thermophilic archaea could soon contribute to the future of bioleaching in commercial operations.

Current biomining processes

Commercial-scale biomining for metal recovery primarily employs two process types: irrigation-type and stirred tank-type systems. Irrigation-based methods involve the percolation of leaching solutions through crushed ores or concentrates, typically arranged in columns, heaps, or dumps. This approach may also be applied in situ, where ore is treated without excavation. In contrast, stirred tank processes utilize continuously operating, highly aerated bioreactors, providing a controlled environment for microbial activity. A defining characteristic of both systems is the absence of sterilization protocols, distinguishing them from conventional industrial fermentation. This is feasible due to the extreme conditions—particularly high acidity created by chemoautotrophic, acidophilic microbes, which inhibit the growth of competing organisms.

Furthermore, the biomining process inherently promotes natural selection: only the most efficient mineral-decomposing microorganisms dominate. These microbes exploit the mineral as their sole energy source, ensuring that only highly effective strains persist and proliferate under these conditions.

Future innovations

Future innovations are anticipated to focus on high-temperature processes, potentially operating at 70°C or above to enhance metal recovery from a broader range of minerals. The exploration of microbial diversity and molecular biology has mainly focused on *Acidithiobacillus ferrooxidans*, though significant opportunities lie in studying other genera such as *Leptospirillum* and *At. Caldus*, which remain underexplored. Future advances will likely involve the use of thermophilic archaea, which are better suited for high-temperature operations. These organisms are crucial for improving metal solubilization, especially in copper recovery from refractory ores like chalcopyrite. A key challenge is the isolation of iron- and sulfur-oxidizing thermophiles that are resistant to high metal concentrations and mechanical stress. Standard microbiological techniques often fall short for these extremophiles, particularly in culturing, mutant isolation, and transformant selection. Nevertheless, with the advent of new molecular tools (e.g., genomics and proteomics), these high-temperature organisms represent a promising and largely untapped frontier in biomining.

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