BIOHYDROMETALLURGY

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Contents

1. Introduction
1.1. General
1.2. Historical Development
1.3. The Future of Biomining Technologies
2. Microbiology of Biomining Processes
2.1. Leaching Bacteria
2.2. Leaching Mechanisms
2.3. Kinetics of Ferrous Ion Oxidation
3. Effect of Operation Variables
3.1. Nutrients and Inhibitors
3.2. Gaseous Nutrients
3.3. Effect of Temperature and pH
3.4. Mineral Composition and Particle Size
3.5. Operation Mode
4. Bioleaching of Copper
4.1. Copper Mining
4.2. Copper Bio-Mining
5. Bio-Oxidation of Gold Ores
5.1. Gold Mining
5.2. The Bio-Oxidation Process
Glossary
Bibliography
Biographical Sketch

Summary

The term biohydrometallurgy refers to the application of microbial technologies to the exploitation of mineral ores. Bacterial leaching is the solubilization of one or more components of an ore by the action of microbial cells. The term bio-oxidation applies to the process used in gold mining in which the oxidation of accompanying sulfides facilitates the recovery of gold. In this case the product of interest, gold, is not involved in the bio-process. The microorganisms that mediate these processes obtain their metabolic energy from the oxidation of sulfides and ferrous ions. In this way insoluble sulfides are oxidized to soluble sulfates of heavy metals. Chemolithoautotrophic mesophilic bacteria of the genera *Thiobacillus* and *Leptospirillum* are the most commonly found leaching organisms. Moderate thermophilic bacteria and extreme thermophilic archeons are gaining attention as leaching agents. Two mechanisms have been postulated to explain the microbial action, namely, the direct and the indirect

mechanisms. In the direct mechanism the microbial cells oxidize the sulfides to sulfates. In the indirect mechanism the oxidizing agent is the ferric ion, whereby the bacterial population oxidizes the products of the ferric attack, elemental sulfur and ferrous ion, to soluble sulfate and ferric ion, with the latter being used for further mineral oxidation. When applied to large-scale operation, bio-leaching can be carried out in heaps, dumps, *in situ* or in reactors. The process is depending on the nature of the microbial population, the kind of ore, its particle size, temperature, pH, Eh, availability of nutrients, presence of inhibitory substances, and supply of oxygen and carbon dioxide. The largest current commercial applications of biohydrometallurgy are in copper and gold mining. Copper bio-mining employs heap and dump operations, while the bio-oxidation of gold is performed in tank reactors, when concentrates are processed, and in heaps for crude ores.

1. Introduction

1.1. General

Bacterial technologies for the treatment of metal ores have received increasing attention in the past few years as an interesting alternative to traditional technologies. The use of bacteria has been proposed for several different mining and related processes, for example, leaching of sulfides and insoluble oxides, desulfurization of coal and oil, bio–sorption of metal ions, oil tertiary recovery and recovery of shale-oil.

In a general sense, leaching is the preferential solubilization of one or more components of a solid matrix by contact with a liquid phase. In the case of bacterial leaching of minerals, also called bio-leaching, the solubilizing agents are bacteria. In bio-leaching, part of the bacterial population is suspended in the liquid phase and the rest attaches to the mineral surface. In what follows, a distinction will be made between the terms bacterial leaching or bio-leaching and bio-oxidation. Bacterial leaching will refer to processes by which the metal ion of interest is extracted from the ore by bacterial action, for example, bacterial leaching of copper. Bio–oxidation will imply the bacterial oxidation of reduced sulfur species accompanying the metal of interest, such as the bio–oxidation of refractory gold minerals.

Bacteria of different genera and species participate in the bio–leaching processes. In actual operations the most commonly found bacteria belong to the genera *Thiobacillus* and *Leptospirillum*. *Thiobacillus ferrooxidans* is always present in mine acid waters and is the most widely studied leaching bacterium. Also important are *Thiobacillus thiooxidans* and *Leptospirillum ferrooxidans*. Currently there is an increasing interest in thermophilic organisms, most of them belonging to the archaea domain (see *Biotechnological Potential of Archae*).

Originally, bio-leaching was thought to be a technology suitable only for the recovery of metals from waste materials, such as flotation tailings, or from very low–grade ores that could not be economically processed by conventional metallurgical technologies. This perception has changed in the last 15 years or so. During this period several large-scale bio-mining operations have been established in which bacterial processes are used in the main production line. This is the case in some important copper mines in Chile and in the majority of the gold mines that have been installed since 1986 for the treatment of refractory ores.

Compared with the traditional extractive metallurgical technologies for the treatment of sulfides, bacterial leaching appears to be an attractive and simple alternative with advantages in capital investment, the use of energy, and preservation of the environment. As an alternative to roasting and high pressure oxidation, the bio-oxidation presents the same mentioned characteristics, to which the mild operational conditions in respect to temperature and pressure should be added.

Large-scale bio-leaching operations can be performed in heaps, dumps, vats, *in situ*, or in reactors. In heap operations, the ore is ground to an appropriate size and arranged in large heaps that are irrigated with an acidic liquor containing the bacteria. The liquor percolates through the mass of mineral and is recycled until an adequate concentration of the metal of interest is attained. Dump leaching is similar, except that dumps of discarded or spent material are used instead of heaps. In *in situ* operation, the metal is leached out from the ore in its original position in the mine by drilling holes and injecting the liquor at high pressure. The rich liquor is collected at some lower point or through drilled holes. In a similar operation mode, sometimes called in-place operation, the ore is fractured by controlled explosions in its original location, and then irrigated. Stirred reactors may be used, usually operating continuously. Reactors have important advantages over the other configurations as a closer control can be exerted on the process, resulting in increased yields and productivities. The main limitations in the use of reactors are the large quantities of material to be treated, the low reaction rates, and the subsequent need for large reactor volumes. When the volume of the material is moderate, as in the case of gold concentrates, bioreactors can be successfully used. Some important copper mines are evaluating the economical feasibility of using reactors for the treatment of their concentrates.

1.2. Historical Development

Natural bacterial leaching has contributed to mining operations for many centuries, probably since the times of the Roman Empire or before. It has been mentioned that the first large scale copper operation, in which microbial activity played an important role, was the Rio Tinto mine in Spain, in the second half of the eighteenth century. But it was not until 1947 that the role of bacteria was demonstrated, when bacteria of the genus *Thiobacillus* were isolated. Later, in the early 1950s, *Thiobacillus ferrooxidans* and *Thiobacillus thiooxidans* were isolated and characterized.

Until the mid-1980s, biomining techniques were used only for the recovery of copper from spent material such as flotation tailings, or for processing low–grade ores, with quite low annual productions, as shown in Table 1.

Mine	Operation mode	Copper grade %	Bacteria	Production, tonne/year
Duval, Copper Basin (USA)	Dump	0.31	Unknown	2300

Duval, Esperanza (USA)	Dump	0.15-0.20	*T. ferrooxidans*	2500
Bluebird (USA)	Heap	0.5	Unknown	6800
Degtyansky (USSR)	Dump/*In-situ*	No data	*T. ferrooxidans*	900
Kosaka (Japan)	In-situ	0.15-0.25	*T. ferrooxidans*	800
Río Tinto (Spain)	Dump	Variable	*T. ferrooxidans*	8000
Cananea (Mexico)	Dump/*In-situ*	Variable	*T. ferrooxidans*	9000
Santo Domingo (Portugal)	In-situ	No data	*T. ferrooxidans*	670

[a]Gentina, J.C., Acevedo, F. (1985). *Trends in Biotechnology* **3**(4), 86-89.

Table 1. Examples of commercial copper bioleaching operations by the mid-1980s.

This situation began to change in the second half of the decade when Minera Pudahuel in its Lo Aguirre mine switched from acid leaching to bacterial leaching of its mixed copper ores with over 1% Copper (Cu). This mine has been operating from this time combining the bacterial process with solvent extraction and electrowinning, producing approximately 14 000 tonnes of fine copper annually. Since then, no fewer than five large copper mining operations using bioleaching as their main technology have been installed in Chile for treating their medium– or high–grade ores, while several other mines use bioprocesses for copper recovery from spent material.

Another important development occurred in the mid-1980s, when bacterial bio–oxidation of refractory gold concentrates and ores proved to be both technically and economically feasible. Significant increases in gold recovery are obtained by partially dissolving the sulfide film that covers the gold particles in refractory ores, allowing for a better contact between gold and the cyanide extracting solution. Currently over eight gold mines located in South Africa, Ghana, Australia, Brazil and Peru use this technology.

1.3. The Future of Biomining Technologies

The future of bioleaching, biooxidation, and related microbial technologies appears very promising. The current large-scale operations in copper and gold mining have opened a gateway to new commercial applications. The processing of other heavy metals such as nickel, cobalt, zinc, and others, the desulfurization of coal and oil that would allow the use of otherwise highly contaminating fuels, and the recovery of oil from spent wells and shale–oil are examples of attractive possibilities. The use of microbial biomass for adsorption of ions should also be considered in the treatment of mining and industrial effluents.

One very promising field of development, is the use of thermophilic microorganisms, especially extreme thermophiles. These cell populations are able to grow at temperatures of 60 to 70 ºC or higher. Most of these organisms are not true bacteria but belong to the domain of the archea. High leaching rates are obtained and the most recalcitrant species such as chalcopyrite are efficiently attacked, though some problems related to inhibition must be resolved.

The prompt attainment of these goals requires that more basic and applied knowledge be gained in relation to the microbial populations involved and their behavior. The understanding of the physiology and genetics of leaching microorganisms is still far from complete. Important aspects related to metabolic control mechanisms, metabolic routes, genetic map, and adherence phenomena require a better and more complete understanding. On the other hand, more insight is needed in engineering factors such as bioprocess kinetics, reactor design, energy economy, control of the process variables, and process optimization, to name a few.

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bioleaching of gold, copper and non-sulfide ores]

Biographical Sketch

Fernando Acevedo was born in Viña del Mar, Chile, in 1939. He obtained a Chemical Engineering degree at the Catholic University of Valparaíso-Chile (UCV) in 1964 and a Master in Science degree in Biochemical Engineering at the Massachusetts Institute of Technology (MIT) in 1972. He worked for three years in the department of engineering of a major fish processing industry in Iquique, Chile. In 1967 he joined the faculty of the School of Chemical Engineering of UCV. He participated in the project that led to the creation in 1969 of the current School of Biochemical Engineering. He has been Director of the School of Biochemical Engineering for several periods, Dean of Engineering for two periods, Director of Research and Graduate Education of the university for five years. He has been a member of the National Committee of Biotechnology since its establishment in 1983. Currently he is full professor of biochemical engineering. He lectures in food engineering and fermentation engineering for the undergraduate and graduate programs. His research work centers in different aspects of fermentation engineering and technology. He has investigated in bioleaching of minerals for the last twenty-five years. Professor Acevedo's main contributions have been in the fields of microbial growth, fermentation stoichiometry and theoretical yields, continuous culture and bacterial leaching of copper and gold minerals. He has presented over one hundred papers in national and international meetings and has over forty publications in scientific journals and books.