METALS AND MATERIALS International, Vol. 11, No. 3 (2005), pp. 249~256

Bioleaching: A Microbial Process of Metal Recovery; A Review

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The present review describes the historical development and mechanisms of bioleaching. Recent development has shown commercial application of the process and, concurrently, details pertaining to the key microorganisms involved in these processes have been described. Bioleaching of metal sulfides is caused by diverse groups of bacteria. The dissolution biochemistry signifies two types of pathways, which are specifically determined by the acid-solubility of the sulfides, the thiosulfate and polysulfate pathways. This sulfide dissolution can be affected by 'direct' and 'indirect' mechanisms. In the 'indirect' mechanism bacteria oxidize only dissolved iron (II) ions to iron (III) ions and the latter can then attack metal sulfides and then be reduced to iron (II) ions. The 'direct' mechanism requires the attachment of bacteria to the sulfide surfaces. In the case of thiobacilli, bacteria secrete exopolymer that facilitates attachment of the bacteria to a metal surface, thus enhancing the leaching rate. In terms of eco-friendliness and process economics, within the field of bio-hydrometallurgy the technology is considered robust.

Keywords: bioleaching, microorganisms, sulfide minerals, bacteria, mechanism

1. INTRODUCTION

As a consequence of technological and industrial development, many industrial sites are contaminated with heavy metals and organic compounds, which are recognized to be anthropogenic and toxic to many kinds of organisms, particularly human beings. Therefore, industry and government are obliged to implement the concepts of a structured environmental management system more strictly [1,2]. Moreover, the application of environmental biotechnology improves cost and efficiency when microorganisms are exploited to reduce the environmental burden of toxic substances [3]. This endeavor is possible through biotechnology.

Application of biotechnology in mining has been investigated in various research organizations and industries within a large number of countries for the past 40 years.

Today, several technologies have been exploited commercially in well mechanized and engineered systems. These can be grouped under the term biohydrometallurgy. Biohydrometallurgy is comprised of different disciplines which are classified according to the interaction between metals and microbes. The various bio-processing technologies include bioremediation, biosorption, bioaccumulation, and bioleaching. Bioremediation consists of the treatment of acid mine run-off or mine tailings to reduce contaminants affecting natural bodies whereas, biosorption and bioaccumulation readily activate on heavy metals to detoxify the environment where these metals accumulate. Application of microbial technology in the mining industry has shown a progressive development in metal extraction during the twentieth century. This process is commonly referred to as bioleaching. More specifically, the study of microbial consortia of extremely acidic, metal-rich environments has provided the foundation upon which mineral processing technologies have developed [4,5].

This review focuses on the process of bioleaching, a conventional and eco-friendly method for the recovery of metals by application of microorganisms. The solubilization of metals from their ores produces concentrated solutions of metal such as copper, gold, uranium etc., which can be recovered by hydrometallurgical processes. The microbial extraction of metals is done through leaching by acidophilic sulfur oxidizing and iron-oxidizing bacteria.

2. BIOLEACHING – THE TERMINOLOGY

In general, bioleaching is a process described as "the dissolution of metals from their mineral sources by certain naturally occur microorganisms" or the use of microorganisms to transform elements so that the elements can be extracted

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from a material when water is filtered through it [6,7]. Generally, bioleaching refers to the conversion of solid metal values into their water soluble forms by the use of microorganisms. For example, in the case of copper, copper sulfide is microbially oxidized to copper sulfate and metal values are present in the aqueous phase and the remaining solids are discarded. In contrast, 'biooxidation', a variation of bioleaching, describes the microbiological oxidation of minerals which contain metal compounds of interest. As a result, metal values remain in the solid residues in a more concentrated form. Some other terms including 'biomining', 'bioextraction', and 'biorecovery' are also applied to describe the mobilization of elements from solid materials mediated by bacteria or fungi or planktonic residues [8]. Biomining mainly concerns the large-scale application of a microbial process in the mining industry for economical metal recovery.

3. HISTORICAL PERSPECTIVE OF BIOLEACHING

The historical background of metal accumulation in various acid mine drainage, mine dumps, and coal heaps has been reported elsewhere [6]. The leaching of copper from ore and the precipitation of copper from the resultant solution is an ancient technology which the Chinese practiced as far back as 100-200 BC and possibly even earlier [9,10]. The same processes were also known in Europe and Asia Minor, and were likely to be utilized there around the 2nd century [10]. However, the involvement of specific microorganisms in metal solubilization processes was evidently not practiced until the 1940s. Since then many research contributions have helped to clarify the basic mechanism behind this process.

Biooxidation of sulfide ores for copper recovery has been practiced for centuries in Spain, Sweden, Germany, China, and elsewhere by solution mining technologies [11]. However, the Rio Tinto mines in south-western Spain are generally considered the cradle of biohydrometallurgy. These mines have been exploited since pre-Roman times for their copper, gold, and silver values [12]. The use of bioleaching at the Rio Tinto mines was commenced in the beginning of the 1890s. Heaps of low grade copper ore were built and left for 1 to 3 years for natural decomposition [13]. The run-of-mine material of low grade copper, stacked in waste dumps to depths of over 100 m in height, was leached using an acidic ferric iron solution for economic recovery of copper at the Kennecott Bingham Mine near Salt Lake City, Utah. Although industrial leaching operations were conducted at Rio Tinto Mines for several decades, the contribution of bacteria to metal solubilization was not confirmed until 1961, when Thiobacillus ferrooxidans was discovered in the leachates [13]. The acidophilic iron oxidizing bacteria Thiobacillus ferrooxidans was recognized as a means to maintain iron in an oxidized form to serve as an oxidant for sulfide copper ore in order to solubilize copper.

Commercial application of biohydrometallurgy, designed to facilitate the activity of microorganisms, was initiated in 1980 for copper leaching from heaps. Numerous copper heap bioleach operations have been set up since 1980 [14]. It has been reported that the Lo Aguirre mine in Chile processed about 16,000 t ore/day between 1980 and 1996 using bioleaching [15]. Early commercial application of bioleaching technology was processed through sub-marginal grade of copper bearing rock in dumps. Today dump bioleaching remains a very low cost process for extracting copper from rock, which cannot be economically processed by other method. Hence, recent applications of these technologies promote heap bioleaching processes. Another excellent example of a current commercial bioleach application is the Quebrada Blanca operation in Northern Chile [16], which is located at an elevation of 4400 m. Being positioned at such a high altitude, this plant can process 17,300 t of sulfide ore per day. This process illustrates the successful evolution of biohydrometallurgy in the mining industry [15]. Tabulated data of eleven copper bioheap leach plants and one in situ bioleach operation that have been commissioned since 1980 is given below.

Another successful and extensive commercial application of biohydrometallurgy is biooxidation pretreatment of refractory sulfidic gold ores. The biooxidation pretreatment plant with the longest history is commissioned at Goldfields' BIOX process at the Fairview Mine in South Africa. This plant has been operating since 1986, and it treats refractory arsenopyrites/pyrite gold-bearing concentrate in large, stirred tank, aerated, continuous reactors [17,18]. To date, there are six commercial biooxidation (Refractory Gold) plants in South Africa, Australia (3 plants), Brazil, and Ghana. The Sansu project in Ghana is the largest biooxidation plant; it treats 760/tones/day of refractory concentrate in three parallel reactors. The Youanmi project utilizes Bac Tech technology, which uses moderately thermophilic bacterial culture such as Sulfobacillus thermosulfidooxidans and biooxidation takes place between 45 and 55 °C [19]. A commercial heap leaching refractory gold ore plant has been operated by Newmont Mining Corporation, at Gold Quarry Mine, Elko, Nevada [20]. Biooxidation is carried out on crushed ore stacked on pads with an air-ventilation system at the base to supply oxygen to the microbial population inoculated on the rock.

Another innovative process for biooxidation of refractory gold ores integrates the concept of flotation concentrates [21]. This technology, developed by Geobiotics, is called GEOCOAT™ and is currently being operated in pilot scale. The process entails coating refractory sulfide gold concentrates onto a screened support rock or ore. Biooxidation pretreatment takes place in a stacked heap configuration. The oxidized support is then removed from the rock for gold

Table 1. Commercial copper bioheap leach plants

Plant and Location	Size (t/day)	Years in operation
Lo Aguirre, Chile	16,000	1980-1996
Gunpowder's Mammoth Mine, Australia	In situ (1.2 Million tonne)	1991- Present
Mt. Leyshon, Australia	1,370	1992-1997
Cerro Colorado, Chile	16,000	1993-Present
Girilambone, Australia	2,000	1993-Present
Ivan-Zar, Chile	1,500	1994-Present
Quebrada Blanca, Chile	17,300	1994-Present
Andacollo, Chile	10,000	1996-Present
Dos Amigos, Chile	3,000	1996-Present
Cerro Verde, Peru	15,000	1996-Present
Zaldivar, Chile	20,000	1998-Present
S&K Copper Project, Myanmar	15,000	1998-Present

Table 2. Commercial stirred-tank reactor bioleach plants for pretreatment of gold concentrate [20]

Plant and Location	Size (tones concentrate/day)	Technology	Years in operation
Fairview, South Africa	Initially10, Expanded to 35, Expanded to 40	BIOX	1986-Present
Sao Bento, Brazil	Intially 150, Expanded	BIOX Eldorado	1990-Present
Harbour Lights, Australia	40	BIOX	1992-1994
Wiluna, Australia	Initailly 115, expanded to 158	BIOX	1993-Present
Sansu, Ghana	Initially 720 Expanded to 960	BIOX	1994-Present
Youanmi, Australia	120	BacTech	1994-1998
Tamboraque, Peru	60	BIOX	1990-Present
Beaconsfield, Australia	70	BacTech	200-Present
Laizhou, China	100	BacTech	2001-Present

extraction by conventional hydrometallurgical processes. This process has also been tested for bioleaching copper from chalcopyrite concentrate using thermophilic microorganisms [22].

Table 2 lists the existing commercial stirred-tank bioleach plants for pretreatment of refractory gold concentrates. The largest of these operations is Sansu, where nearly 1000 t of concentrate are processed daily in reactors up to 900 m^3 in size.

4. PRINCIPLES OF MICROBIAL METAL LEACHING

Microbially metal-extraction processes are usually more eco-friendly than physico-chemical processes. They do not use large amount of energy as compared to roasting and smelting and do not produce sulfur dioxide or other harmful gases. As such, this process can be considered to be compatible with antipollution laws.

Most naturally occurring bacteria and fungi perform numerous physiologically important reactions that enable them to grow and reproduce. Mineralytic effects of bacteria and fungi on minerals are mainly based on three principles, acidolysis, complexolysis, and redoxolysis. Microorganisms are able to mobilize metals through the following processes:

1. Formation of organic and inorganic acids (proton formation)
2. Excretion of complexing agents (ligand formation)
3. Oxidation and reduction reactions

Generally, sulfuric acid is the main inorganic acid formed in the leaching environment. It is formed by sulfur oxidizing microorganisms such as thiobacilli. Also, a series of organic acids are formed by bacterial and fungal metabolism resulting in organic acidolysis, and complex and chelate formation [23]. Proton induced and ligand-induced mineral solubilization occurs simultaneously in the presence of ligands under acidic conditions.

The biooxidation of reduced iron to generate ferric(III) iron by chemolithotrophic bacteria in slightly acidic conditions is a well known phenomenon. Ferric ion is a strong oxidizing agent that is responsible for mineral sulfide dissolution. The ferric iron is reduced during the reaction but the effective microbes ensure continuous regeneration of ferric ions. Also, many strains have the ability to reduce ferric (III) ions to ferrous (II) ions in anaerobic conditions. The process can be expressed as follows:

$$2Fe^{+2} + 2H^{+} + \frac{1}{2}O_2 \rightarrow 2Fe^{+3} + H_2O \quad (1)$$

$$CuFeS_2\ (\text{Chalcopyrite}) + 4Fe^{+3} \rightarrow 5Fe^{+2} + Cu^{+2} + S^0 \quad (2)$$

5. MECHANISMS OF BIOLEACHING

Initially, a model involving two mechanisms was proposed to explain the microbial metal solubilization of sulfide minerals. Microorganisms can oxidize metal sulfides via a direct mechanism where electrons are obtained directly from the reduced minerals. In this case cells have to be attached to the mineral surface and a close contact is needed. The adsorption of cells to suspended mineral particles takes place within some minutes or hours [24,25].

Another mechanism, called the 'indirect' mechanism, the oxidation of reduced metals is mediated by ferric (III) ion and this ferric is formed by microbial oxidation of ferrous iron present in the minerals. Ferric iron acts as an oxidant and can oxidize metal sulfides and is reduced to ferrous iron which, in turn, can be microbially oxidized. In this case iron acts as an electron carrier. It was proposed that no direct physical contact is needed for the oxidation of iron [26].

In many cases it was concluded that the 'direct' mechanism dominates the 'indirect' one, mostly because the direct mechanism involves direct physical contact of bacteria with the mineral surfaces [27]. It has been demonstrated that T. ferrooxidans attaches readily to the surface of metal sulfides. In a direct attack, electron transfer from sulfide-S, or from cuprous copper in the case of Cu_2S, involves Fe(II) bound in the cell envelope and exopolymer [28]. It has been observed that the sites on a metal sulfide particle for bacterial attachment and attack appear to be limited. Thus, once maximum attachment has been achieved, further multiplication of attached cells should result in the displacement into the bulk phase of one of the two daughter cells of each dividing bacterium [29,30]. However, the attachment of microorganisms on surfaces is not an indication of the existence of a direct mechanism. The term contact leaching has been introduced to indicate the importance of bacterial attachment to mineral surfaces [31].

The following equations describe the direct and indirect mechanisms for the oxidation of pyrite [32].

Direct:

$$2FeS_2+3.5O_2+H_2O \xrightarrow{Thiobacillus} Fe^{2+}+2H^{+}+2SO_4^{2-} \tag{3}$$

$$2Fe^{2+}+1/2\ O_2+2H^{+} \rightarrow 2Fe^{3+}+H_2O \tag{4}$$

Indirect:

$$FeS_2+14\ Fe^{+3}+8\ H_2O \xrightarrow{Thiobacillus} 15\ Fe^{+2}+16\ H^{+}+2\ SO_4^{-2} \tag{5}$$

$$MS+2Fe^{+3} \rightarrow M^{+2}+S^{0}+2Fe^{2+} \tag{6}$$

$$S^{0}+1.5\ O_2+H_2O \rightarrow 2H^{+}+SO_4^{2-} \tag{7}$$

However, the model of direct and indirect metal leaching is still under discussion. Recently, this model has been revised and replaced by a model that is not dependent on the differentiation between direct and indirect leaching mechanisms [33,34]. The key aspects of the leaching have been integrated and a mechanism has been developed which is characterized by the following features:

(1) cells have to be attached to the minerals and in physical contact with the surface;

(2) cells form and excrete exopolymers;

(3) these exopolymeric cell envelopes contain ferric iron compounds that are complexed to glucouronic residues. These are regarded as part of primary attack;

(4) Thiosulafte is formed as intermediate during the oxidation of sulfur compounds;

(5) Sulfur or polythionate granules are formed in the periplasmic space or in the cell envelope.

6. MECHANISM OF METAL SULFIDE DISSOLUTION

There are two different reaction mechanisms that control the dissolution of metal sulfides: the thiosulfate pathway and the polysulfate pathway.

In general, dissolution is achieved by a combination of proton attack and oxidation processes. The reaction process is determined by the mineral species [32,35]. The electronic configuration reveals a crystal structure having monosulfide or disulfide structures does not control the pathway of dissolution [35]. Metal sulfides can be categorized depending upon their solubility in acids. These are (i) acid-nonsoluble metal sulfides (thiosulfate pathway), and (ii) acid-soluble metal sulfides (polysulfate pathway).

In the thiosulfate mechanism (Fig. 1(A)), metal sulfides such as pyrite, molybdenite, and tungstenite (FeS_2, MoS_2, and WS_2 respectively) are exclusively oxidized via electron extractions by ferric (Fe(III)) ions. In this group of metal sulfides, the chemical bonds between sulfur and metal moiety do not break until a total of six successive one-electron (iron

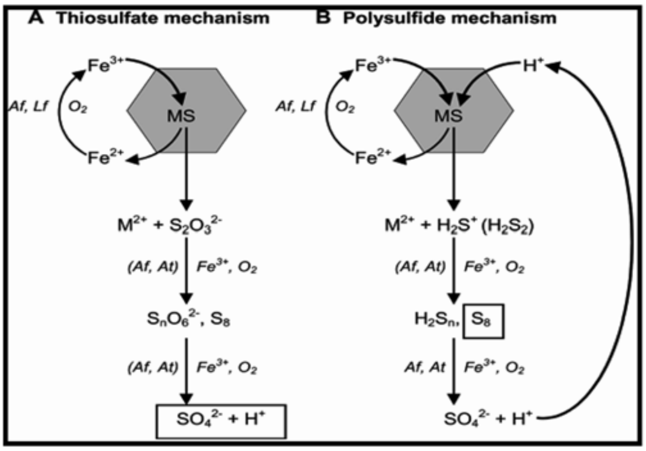

Fig. 1. Schematic representation of the thiosulfate (A) and polysulfide (B) mechanisms.

(III) hexahydrate) oxidation steps have been conducted and thiosulfate is liberated. This mechanism is named after its first free sulfur compound [36-38].

In the polysulfide mechanisms (Fig. 1(B)), metal sulfides such as sphalerite (ZnS), galena (PbS), arsenopyrite (FeAsS), chalcopyrite ($CuFeS_2$), and hauerite (MnS_2) are dissolved by the combined effect of electron extraction by ferric(III) ions and proton attack, i.e., the binding of protons by the sulfide moiety via valence bond electrons. In this group of metal sulfides the chemical bonds between metal and sulfur moiety can be broken by proton attack and, after binding two protons, hydrogen sulfide (H_2S) is liberated. Here, the first free sulfur compound is most likely a sulfide cation (H_2S^+) which can spontaneously dimerize to free disulfide (H_2S_2) and is further oxidized via higher polysulfides and polysulfide radicals to elemental sulfur [39]. Hence, this mechanism was named the "polysulfide pathway".

7. BACTERIAL ATTACHMENT ON METAL SURFACES

It is known that the formation of exopolymeric polysaccharides plays an important role in the attachment of thiobacilli on metal surfaces such as covellite, pyrite, or sphalerite. Extraction or loss of formation of these materials prevents the attachment of bacteria to the metal surface and also decreases the leaching efficiencies [27,40]. Interaction between microorganisms and mineral surfaces occurs on two levels, physical sorption and chemical sorption [41]. In physical sorption, due to the low pH of the leaching environment, microbial cell envelopes are positively charged, leading to electrostatic interaction with the mineral surface. In chemical sorption, there a chemical bond develops between cell and minerals (disulphide bridges). In addition to this, extracellular metabolites are also formed during this phase near the attachment [26]. Sulfur oxidizers excrete low molecular weight metabolites, which mostly contain acids of TCA cycle, amino acids, or ethanolamine and high molecular weight compounds such as lipids and phospholipids [41]. It has been observed that in the presence of elemental sulfur, sulfur-oxidizing microorganisms form a filamentous matrix similar to bacterial glycocalyx, suggesting the relative importance of these extracellular substances in the colonization of solid particles [42].

8. MICROBIAL DIVERSITY IN BIOLEACHING ENVIRONMENTS

The predominant metal-sulfide dissolving microorganisms are extremely acidophilic bacteria (thriving at pH below 3), also known as chemolithotrophs, which utilize either reduced inorganic sulfur or ferrous (II) iron (some use both) as an energy source and grow autotrophically by fixing CO_2 from the atmosphere. Also, some organisms have been found to grow better when provided with air that has been enriched with 0.5-5 % (v/v) carbon dioxide [43,44].

The classical leaching bacteria belong to the genus Acidithiobacillus (formerly called Thiobacillus), which are generally gram-negative γ-proteobacteria. These include the iron and sulfur oxidizing Acidithiobacillus ferrooxidans, the sulfur oxidizing At. thiooxidans, At. caldus, and the iron-oxidizing Leptospirillum ferrooxidans and L. ferriphilum [45,46]. These bacteria are usually regarded as mesophilic, i.e., they carry out biooxidation at 40 ^{o}C or less. Gram-positive leaching bacteria are moderately thermophilic members of the genera Acidimicrobium, Ferromicrobium, and Sulfobacillus [43,47]. Leaching archaebacteria have been known for many years and all belong to the Sulfobales, a group of extremely thermophilic sulfur and iron oxidizers including genera such as Sulfolobus, Acidianus, Metallosphaera, and Sulfurisphaera [48,49]. Recently, mesophilic and acidophilic iron oxidizing archaebacteria have also been discovered. These belong to Thermoplasmales; two species, Ferroplasma acidiphilum and F. acidarmanus [50], are known.

Among these bacteria there are species of limited substrate spectrum. Particularly, L. ferrooxidans and L. ferriphilum can grow only by aerobically oxidizing iron (II) ions. In contrast, At. ferrooxidans is endowed with a broad metabolic capacity. This species lives on the oxidation of reduced sulfur compounds and is able to oxidize molecular hydrogen, formic acid, ferrous (II) ions, and other metal ions. Anaerobic growth is possible by oxidation of sulfur compounds or hydrogen coupled with iron (III) ion reduction [51-53]. Recently it was discovered that At, ferrooxidans, like Acidianus spp., reduces elemental sulfur in the course of anaerobic hydrogen oxidation [53]. The application of electron acceptors other than oxygen is reflected by the presence of various electron transport components. In the case of Acidithiobacillus ferrooxidans, at least 11 different types of cytochrome c types have been investigated [54]. Since these leaching bacteria control the aerobic and anaerobic iron and sulfur oxidation processes, they could have especially great importance for AMD treatment. In natural processes, where bioleaching in waste heaps and tailings is topped by flooding or with organic covers, both common AMD create an anoxic environment, and in this condition leaching bacteria could remain active due to their anaerobic capacities. The resulting anaerobic leaching of pyrite and other metal sulfides at low pH values is still under investigation. However, the aforementioned anaerobic physiology of leaching bacteria and their presence in anoxic biotopes support the hypothesis of an anaerobic leaching process. For example, the existence of Acidithiobacillus-like species has been demonstrated in an anoxic reactor designed to clean contaminated ground-water and lignite. Also, a carbon assimilation pathway detects the metabolic diversity of these bacteria to some extent.

Acidithiobacillus spp. and Leptospirillum spp. are the only chemolithotrophautotroph, whereas Acidiphilium acidophilum and Acidimicrobium ferrooxidans are able to grow autotrophically with sulfur and iron compounds, heterotrophically with glucose and yeast extract, and mixotrophically with all of these substrates [43,55]. In addition, several Acidiphilium spp. and Acidisphaera rubrifaciens possess pigments that may confer photosynthetic activity [55,56].

There have been relatively few reported studies on microorganisms that dominate bioleaching consortia at a temperature of 50 °C. The types of microorganisms found in heap leaching are similar to those found in stirred-tank leaching processes, with At. ferrooxidans, At. thiooxidans and L. ferrooxidans being most frequently detected [57,58]. However the properties of these bacteria vary according to the operating conditions of the heap. At temperatures more than 70 °C, the biomining consortia are dominated by archea rather than by bacteria, with species of Sulfolobus and Metallosphaera being most prominent [49].

9. ECONOMICS OF BIOLEACHING

The economics of any new process technology must be assessed relative to those of existing technologies. Hence, bioleaching is now applied on a commercial scale for leaching of copper and refractory gold ores and concentrates. The utility of bioleaching for uranium has been demonstrated in large scale [59]. However, the capital costs of bioleaching can be divided into association of construction and provision services, operating costs, and supplement of reagents and services. Generally, the capital costs of bioleaching are less than those of conventional chemical methods and smelting and roasting. It is noteworthy that the capital costs for each different type of application of bioleaching processes normally increases in the following order:

Dump < Vat < Heap < Agitated reactor

10. OPERATING COSTS

The operating costs for a bacterial oxidation process include the major categories of power, reagents, services, and labor. Except for the extraction of metal, no other products can be obtained in this process. However, the generation of low grade acid contaminated with dissolved metals and salts can be observed.

Bioleaching is a relatively simple technology that does not require significant instrumentation or sampling to provide high metal recovery. The services that must be provided for assaying, instrument engineering, and maintenance are typically less than for the alternative processes treating similar sulfide materials. The lower levels of these services required by the bioleaching process reduce the operating costs.

Minimal process instrumentation is needed; only pH, dissolved oxygen, and temperature measurement are required. Furthermore, the adjustments of the conditions can be made manually by the operators. Since the process operates at temperature and pressure close to ambient, the maintenance costs of the conventional design are low compared to those of alternative technologies such as pressure oxidation and roasting.

Lastly, since microorganisms are applied in the metal extraction process, the costs can be reduced in terms of handling environmental problems associated with hydrometallurgical processes.

11. FUTURE DEVELOPMENTS

According to Rawlings [8] “much of the future biomining is likely to be hot”. Utilization of thermophilic bacteria and thermophilic archea is gaining significant attention for commercial applications. Pilot scale test work shows extreme thermophiles achieve efficient bioleaching of primary copper sulfide and nickel sulfide concentrates, yielding higher recoveries than those achieved by bioleaching with either mesophilic or moderatethermophilic cultures. BHP-Billiton is actively developing proprietary technologies for stirred-tank bioleaching of chalcopyrite concentrates [60]. BacTech/Mintek with Industrias Penoles of Mexico recently operated a stirred-tank bioleach pilot plant (170 m^3 capacity) in Monterrey, Mexico using moderately thermophilic microorganisms [61]. The project focused on a polymetallic (chalcopyrite, sphalerite, galena) concentrate containing precious metals. Recoveries of 96–97 %Cu, 99 %Zn, 98–99 %Au, and 40 %Ag were achieved at a feed rate of 2.7 t/day. Stable closed-circuit operation was maintained and 0.5 t/day of high purity copper cathode was produced. Bioleaching of “dirty” concentrates, which have high smelter penalty costs, represents some of the most attractive new applications for stirred reactor bioleaching. In addition to stirred reactors, bioleaching of copper from chalcopyrite ore in heaps using thermophiles will likely become a reality within the next few years. The GEOCOAT process, developed by Geobiotics, Lakewood, Colorado, is a unique heap leach system for biooxidation pretreatment of refractory precious metal concentrates and bioleaching copper, zinc or nickel sulfide concentrates. Electrochemical interactions in the bioleaching of complex sulfides could be taken an advance seat in the metal extraction process [62]. Mobilization of metals from electronic waste materials through the bioleaching process robustly helps waste management in the electronic and galvanic industry [63]. Mining industries also recognize that biotechnology offers another tool for economic recovery of metal values. Recovery of metals from different wastes such as industrial sludge, galvanic wastes, and electronics wastes is another milestone of the bioleaching process in this century. Hence, future development will expand the role of biotechnology in the extraction and recovery of many metals.

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