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Life in heaps: a review of microbial responses to variable acidity in sulfide mineral bioleaching heaps for metal extraction

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Abstract

Industrial heap leaching of low grade mineral sulfide ores is catalysed by the use of acidophilic microorganisms. These microorganisms obtain energy for growth from the oxidation of reduced inorganic or organic compounds, including soluble ferrous ion, reduced inorganic sulfur compounds (RISC) and acid-stable organic compounds. By-products of these oxidative processes, such as soluble ferric ion and sulfuric acid create favourable chemical conditions for leaching. This review is focused on the behaviour of common bioleaching microorganisms, their responses to changing pH in an industrial setting, and how both changes and microbial responses can impact the micro and macro environment.

Keywords: Acid stress; Chemolithotrophs; Acidophiles

1. Introduction

Heap (dump and *in situ*) leaching technologies were developed for the processing of ores where metal values are too low or otherwise not suited to flotation concentration and higher-intensity pyrometallurgical processing. Thus, heap leaching is mainly applied to low-grade ores such as secondary copper sulfides, pyritic gold ores or nickel or nickel-copper sulfide ores [1–3]. The technology is well established and accepted by the mineral processing industry and has been practiced in such diverse climates as the South American Andes (Fig. 1), near the Arctic Circle and in the tropics [1,4,5].

The technology is simple and based on natural, microbially-assisted processes first described more than 2000 years ago and today termed acid rock drainage (ARD). Some recent accounts of modern heap practice and the perceived economic benefits have been published [1,6,7]. Briefly, heaps are dynamic systems in which the substrate (sulfide) content diminishes with time, acid is consumed by gangue minerals but periodically augmented to maintain the leaching environment, giving rise to variations in solution pH. Secondary minerals may precipitate, changing the nature of particle surfaces or releasing/consuming acid during their formation. Thus microorganisms are subject to fluctuating solution acidity and substrate availability over the course of mineral sulfide dissolution.

Metals extraction relies upon heap microorganisms to accelerate otherwise slow reactions in which the metal-oxygen bonds in sulfide minerals are broken and the minerals dissolved to their components [6]. Very slow mineral sulfide dissolution can occur via the action of strong acid (e.g., for chalcopyrite, reaction (1)). Faster dissolution is achieved through the action of ferric ion, an oxidant, in an acidic sulfate medium (e.g., for covellite, reaction (2)).

$$CuFeS_2 + O_2 + 4H^+ \rightarrow Cu^{2+} + Fe^{2+} + 2S^0 + 2H_2O \qquad (1)$$

$$CuS + 2Fe^{3+} \rightarrow Cu^{2+} + 2Fe^{2+} + S^0 \qquad (2)$$

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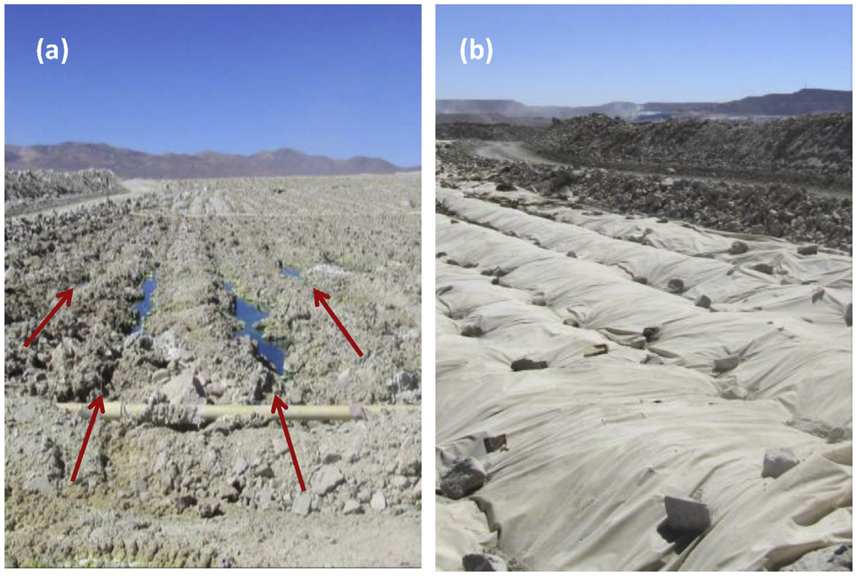

Fig. 1. The run-of-mine dump bioleach at Escondida, Chile, is the largest 'bioreactor' in the world, with a surface area 10^7 m^2 and ore stacked in 18 m lifts to a planned final height of 125 m. (a) surface with irrigation lines and (b) covers to retain heat and moisture. Arrows indicate the distribution and direction of irrigation lines, also evidenced by surface ponding (Images provided by D. Shiers, CSIRO Mineral Resources. Images were previously published in open access article [36]).

The main reactions through which acidophiles contribute to accelerated extraction are the oxidation of ferrous ion and sulfur, the products of sulfide dissolution (reactions (3) and (4)). Note that reaction (3) is acid consuming and reaction (4) is acid generating and that through these two reactions both the required oxidant (ferric ion) and acid are replenished in the process water. Heterotrophs and mixotrophs contribute through the utilisation of organic compounds that may inhibit the activities of some chemolithotrophs (e.g., glucose, reaction (5)).

$$4Fe^{2+} + 4H^+ + O_2 \rightarrow 4Fe^{3+} + 2H_2O \quad (3)$$

$$2S^0 + 3O_2 + 2H_2O \rightarrow 2H_2SO_4 \quad (4)$$

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O \quad (5)$$

Under anaerobic conditions ferric ion reduction can take place, coupled with sulfur or organic compound oxidation (reactions (6) and (7)). Reactions (3)–(7) provide energy for microorganisms, dependent upon their metabolic capabilities.

$$24Fe^{3+} + C_6H_{12}O_6 + 6H_2O \rightarrow 24Fe^{2+} + 6CO_2 + 24H^+ \quad (6)$$

$$6Fe^3 + S^0 + 4H_2O \rightarrow 6Fe^{2+} + 8H^+ + SO_4^{2-} \quad (7)$$

The isolation and characterisation of acidophiles from acidic mine drainage and other acidic metalliferous environments have been the foundation for numerous studies on microbial behaviours. These may be laboratory or larger-scale studies to examine the impacts of various parameters, such as process water composition and acidity, mineral compositions and impurities, and other solution chemistry parameters (oxidation-reduction potential (ORP), ionic strength). In this review some effects of variable acidity on substrate utilisation, attachment and microbial populations are discussed in the context of heap leaching, including: (i) a summary of the acidophiles that have been isolated from, or putatively detected, in heaps and the mechanisms that can be employed to protect them against acid stress; (ii) substrate utilisation responses to variable pH and how this can be used to maintain microbial viability; (iii) the importance of microbial attachment to sulfide minerals and the impacts of pH; (iv) the effects of pH on microbial community compositions, and (v) the impact of pH on microbial activity during leaching. Knowledge of the responses of microorganisms to acid stress will assist in interpreting and/or managing some problems arising during metal production from changeable sulfide-heap environments.

2. Acidophiles in heaps and waste dumps

There is no formal definition of what constitutes an acidophile [8], but rather a general consensus that an acidophile has an optimal pH (pH_{OPT}) for growth significantly lower than pH 7, while an acid-tolerant microorganism has a pH_{OPT} for growth closer to neutral pH. A further subdivision into "moderate acidophile" with pH_{OPT} for growth in the range pH 3–5, and "extreme acidophile" with pH_{OPT} for growth of pH <3 has been proposed [9].

Acidophiles can be grouped according to their adaptation to the acid environment (pH minima and maxima for growth) and to the substrates from which they gain energy for metabolic processes, oxidation of ferrous ions or RISC, or utilisation of organic carbon compounds (Table 1). These simple groupings ignore other equally important categories, such as temperature (psychrophiles, mesophiles, moderate thermophiles, thermophiles or hyperthermophiles), or method of obtaining carbon