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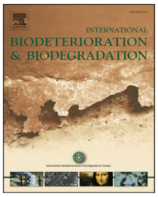

Review

A review of sulfide minerals microbially assisted leaching in stirred tank reactors

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ABSTRACT

Compared to conventional extractive techniques, bacterial assisted leaching, also called "biomining" is an eco-friendly technology that provides improved metal/solid separations. These separations are enhanced by the synergistic activities of astonishingly diverse groups of microorganisms, which lead to an extraction process with low energy consumption, low capital investment and low impact on the environment. Recently, biomining has received great attention in a variety of niche areas, especially in the mineral industries and solid industrial waste materials (e.g. galvanic sludge, sewage sludge, fly ash, electronic waste, spent petrochemical catalysts, medical waste, spent batteries, waste slag) where the metals values are low, or where the presence of certain elements would lead to smelter damage, or where environmental considerations favor biological treatments options. It allows the recovery of metal from low-grade sulfide ores and concentrates that cannot be processed economically by conventional techniques, as well as the production of concentrated metal salt solutions, which could be recycled. Bacterial assisted leaching processes are based on the ability of certain microorganisms to solubilize/or expose the metals contained in the ores and concentrates by direct oxidation, or through indirect chemical oxidation instigated by the corrosive metabolic by-products generated by an electrochemical option, or a combination of both of these. The valuable metals in solution can be recovered using conventional hydrometallurgical techniques. If the material of interest constitutes part of or is in the pretreated residue then it can be further processed for metal recovery.

The majority of microorganisms involved in bacterial assisted leaching processes are chemolithotrophs. Carbon dioxide (CO_2) and oxygen (O_2) are essential nutrients that are used by microorganisms for their growth, maintenance, metabolite production, and survival.

This literature review aims to provide a fundamental understanding of the various mechanisms involved in microbial leaching of sulfide minerals and provide a brief look at the various factors affecting this process. Special attention is focused on the mass transfer rates in the gas phase and how they exert a pivotal role in microbially assisted leaching of sulfide minerals. Also reviewed are the major parameters that can affect gas phase mass transfer, with particular emphasis on how it is related to the efficiency of bacterial assisted leaching.

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1. Introduction

The global trend towards urbanization and industrialization supports the increasing demand for industrial metals. Moreover, the overall global reserves of high-grade ores are close to depletion (Anjum et al., 2012). In this context, low-grade, complex ores, old waste deposits related to past mining activities, and other secondary sources have received much more attention in recent years (Kutschke et al., 2014). For both environmental and economical exploitation of such ores and resources, efficient technologies for the recovery of metals need to be developed and in this area, bacterial assisted leaching is a promising emerging technology.

Sulfide minerals ores such as pyrite (FeS_2), chalcopyrite ($CuFeS_2$), sphalerite (ZnS), galena (PbS) and pentlandite $(FeNi)_9S_8$ are the major sources for recovery of associated metal values (Olson et al., 2003; Jerez, 2011; Schippers et al., 2014) such as gold (Kaksonen et al., 2014), uranium (Abhilash et al., 2011; Abhilash and Pandey, 2013), and silver, and other base metals (Ehrlich, 1997; Brierley and Brierley, 2001; Olson et al., 2003; Viera et al., 2007; Schippers et al., 2014) such as cobalt (D'Hugues et al., 1997; Morin and D'Hugues, 2007), copper (Watling, 2006; Domic, 2007; Pradhan et al., 2008; Watling et al., 2009), nickel (Watling, 2008) and zinc (Konishi et al., 1992; Rodríguez et al., 2003a,2003b; Shi et al., 2006).

Initially it was thought that the dissolution of metals from ores was purely a chemical process, mediated by water and atmospheric oxygen, until the discovery of oxidizing microorganisms which were proven to catalyze/accelerate the mineral dissolution process and, consequently, to solubilize/or expose and recover the target metals (Rudolfs, 1922; Colmer and Hinkle, 1947; Colmer et al., 1950; Temple and Colmer, 1951; Corrans et al., 1972; Torma, 1977; Brierley, 1978, 1982, 1990; Suzuki, 2001; Tributsch and Rojas-Chapana, 2007). The extraction of metals by means of microorganisms, commonly referred to as “biomining”, is an ecologically alternative to conventional pyrometallurgical and chemical metallurgy processes for metals recovery. The principal benefits of the “biomining” process compared to conventional extractive technologies are their lower labor and energy requirements, lower capital investment and reduced harm to the environment (Torma and Banhegyi, 1984; Gentina and Acevedo, 1985; Bruynesteyn, 1989; Acevedo et al., 1993; Agate, 1996; Poulin and Lawrence, 1996; Das et al., 1999; Clark et al., 2006; Johnson, 2013, 2014; Vainshtein, 2014). “Biomining” is a generic term that encompasses both mineral “bioleaching” and “biooxidation” processes (Rawlings, 2002; Rohwerder et al., 2003; Olson et al., 2003; Ehrlich, 2004; Johnson, 2013, 2014). These terms are sometimes used interchangeably, however, “bioleaching” should be used to refer to the conversion of an insoluble metal into a soluble form (e.g. from a metal sulfide into a metal sulfate), thereby extracting the target metal into an aqueous solution. By contrast, mineral “biooxidation”, refers to microbial decomposition of the mineral matrix that occludes or locks the target metal (typically gold and silver) and exposing this entrapped metal making it more accessible for chemical extraction. In these cases, the target metal is not solubilized during the biological process and subsequently requires the use of conventional techniques (e.g. cyanide leaching) for recovery of this metal (Rawlings, 2002, 2004; Johnson, 2013, 2014). However, both “bioleaching” and “biooxidation” processes, used to recover metals from minerals ores and concentrates, were mediated by using essentially the same principals and a similar consortia of microorganisms (Rawlings and Johnson, 2007; Johnson, 2014).

During the last decades, bacterial assisted leaching has seen much development with two main types of processes (irrigation-type (*involving* in situ, *dump, heap and vat leaching*) and stirred tank-type processes) and both have achieved industrial commercial-scale (Rawlings, 2002). A variety of full scale bacterial assisted leaching installations are in operation today, significantly contributing to the amounts of metals mined worldwide. At present, approximately 15–25% of the world's copper production, 5% of gold and smaller percentages of cobalt, nickel, uranium and zinc are currently recovered by bacterial assisted leaching processes (Puhakka et al., 2007; Brierley, 2008; Johnson, 2013; Kutschke et al., 2014; Schippers et al., 2014).

In recent years, several researches have investigated the other practical applications of bacterial assisted leaching in solid wastes from many various industrial sectors such as electroplating, metal-finishing, steel and non-ferrous processes, petrochemical, pharmaceutical, sewage sludge, fly ash from municipal incinerators, and electronic wastes (Krebs et al., 1997; Brandl and Faramarzi, 2006; Cui and Zhang, 2008; Pathak et al., 2009, 2014; Guo et al., 2010; Hoque and Philip, 2011; Lee and Pandey, 2012; Erüst et al., 2013; Mishra and Rhee, 2014; Guezennec et al., 2015).

An important challenge of biohydrometallurgy will be to exploit refractory resources such as complex polymetallic concentrates, low-grade ores and concentrates, and various oxides. The bioleaching operation must be matched to the available resources that