Trends in Biotechnology

Review

Biological and Bioelectrochemical Recovery of Critical and Scarce Metals

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Metal-bearing solid and liquid wastes are increasingly considered as secondary sources of critical and scarce metals. Undoubtedly, microorganisms are a cost-effective resource for extracting and concentrating diffuse elements from secondary sources. Microbial biotechnology for extracting base metals from ores and treatment of metal-laden wastewaters has already been applied at full scale. By contrast, microbe–metal interactions in the recovery of scarce metals and a few critical metals have received attention, whereas the recovery of many others has been barely explored. Therefore, this article explores and details the potential application of microbial biotechnologies in the recovery of critical and scarce metals. In the past decade bioelectrochemical systems have emerged as a new technology platform for metal recovery coupled to the removal of organic matter.

Trends

Overview of potential applications of microorganisms in critical metal recovery.

Engineering of microbe–metal interactions for recovering rare earth elements and platinum group metals.

Reductive mineral dissolution is a new dimension to biomining.

Bioelectrochemical systems offer a new technology platform in metal recovery.

Precious Pollutants

Contamination of natural resources with metal ions is increasingly reported worldwide. Although both natural and anthropogenic activities contribute to metal mobilization, the extent of metal contamination through the anthropogenic route is of concern [1]. Wastewaters containing metal ions are generated in various anthropogenic activities (mining, metallurgical operations, burning fossil fuels, cement production, electroplating, leather tanning) and products (manufacturing plastics, fertilizers, pesticides, anticorrosive agents, Ni-Cd batteries, paints, pigments, dyes, photovoltaic devices) [2]. Metal contamination is a serious concern because metals are (i) not biodegradable, unlike organic pollutants; (ii) toxic and metal ions can undergo transformations to potentially toxic and carcinogenic compounds; and (iii) transfer across the trophic levels of the food-chain, reaching higher trophic levels and bioaccumulating in living organisms. Therefore, metal(loid)s such as silver (Ag), arsenic (As), beryllium (Be), cadmium (Cd), chromium (Cr), copper (Cu), mercury (Hg), nickel (Ni), lead (Pb), antimony (Sb), selenium (Se), thallium (Tl), and zinc (Zn) are included in the US priority pollutants list [3], and stringent limits are in place for regulating discharge of various metals in industrial wastewaters to minimize contamination of natural resources.

Aside from pollution, metals are precious raw materials to the economy of a country and need to be secured for sustainable production of key components of various products such as low-carbon energy technologies, automobiles, and electronic and biomedical devices [4]. Low-carbon energy technologies, catalytic processes, and electronic gadgets require large amounts of critical and scarce metals including platinum group metals (PGMs), rare earth elements (REEs), cobalt, selenium, and tellurium [5]. The availability and supply of **critical metals** (see Glossary) greatly influence the economy of a country by affecting manufacturing, export, and job creation [6]. Most of the critical and scarce metals are currently obtained through mining of

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primary sources such as mineral ores, which are finite, unequally distributed in the world, and rapidly dwindling as a result of urbanization, increasing standards of living, and the population explosion. Many other elements which are presently scarce may thus become critical in the near future. There is thus an urgent need to source these critical and scarce elements from alternative sources using sustainable technologies. Potential alternate sources that are intensely considered include mining from seawater and seafloor [5], recycling from end-of-life metal wastes (e.g., computers, printed circuit boards, smart phones, batteries) and recovery from mine tailings and wastewaters [7]. In particular, solid wastes including electronic waste (e-waste) as well as process streams and wastewaters from the mining and metallurgical sector are a potential secondary source for recovering scarce elements [8,9].

Microbe–metal interactions have been well documented (Figure 1) in both natural and engineered settings. They are studied in different branches of metal biotechnology, including **biomining**, bioremediation, wastewater treatment, and microbiologically influenced corrosion [10], that led to the development of biotechnological processes for the extraction of metals from ores, bioremediation of contaminated sites, treatment of metal-containing wastes, recovery of metals, and mitigation of biocorrosion. Full-scale biotechnological processes have been established for industrial operation to extract base metals from ores in biomining [11] and the treatment of metal-containing waters [12]. In recent times, microbe–metal interactions have received renewed attention as a route to develop sustainable biotechnological metal-recovery processes for solubilization from low-grade ores and solid wastes as well as via metal immobilization from leachate solutions, process streams, and wastewaters (Figure 1).

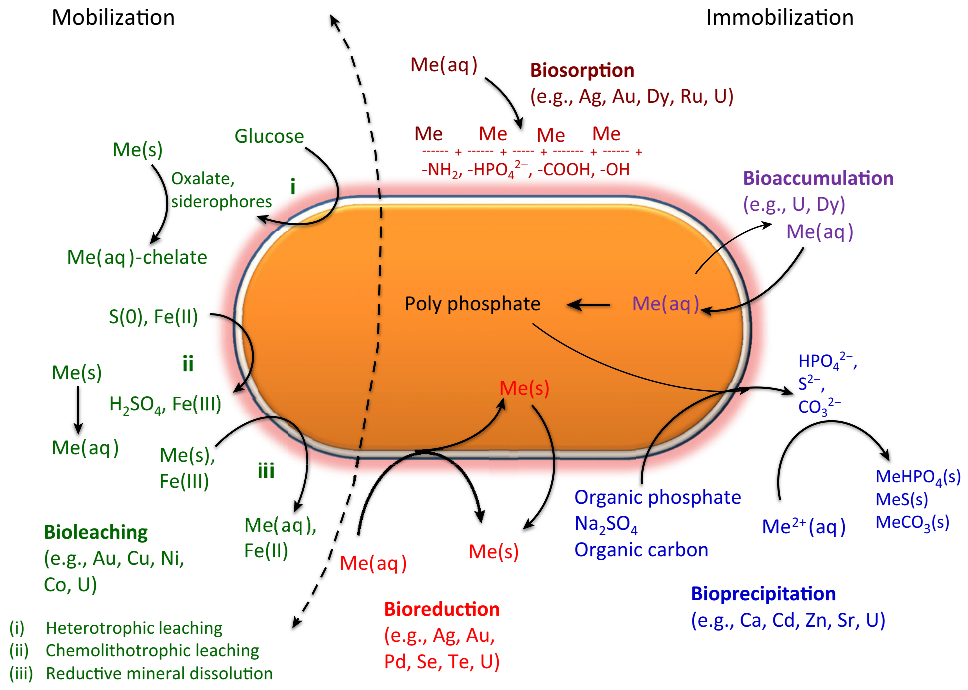

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Figure 1. Microbe–Metal Interactions Depicting Different Mechanisms of Metal Solubilization and Immobilization Used for Biorecovery. In the bioleaching step (autotrophic and heterotrophic leaching of sulfidic ores, reductive dissolution of oxide ores) metals are released into aqueous solution through solubilization of ores or solid concentrates. Processes such as biosorption, bioaccumulation, bioprecipitation, and bioreduction enrich the dissolved metals of leachate streams or diffuse metals of wastewaters as solid precipitates for further metallurgical processing. Abbreviation: Me, metal.

Glossary

Acidophiles: microorganisms which have a pH optimum for growth at or below pH 3.0. Several microorganisms, particularly fungi, can tolerate an acidic pH below 3, but many have an optimum pH for their growth at near neutral pH. Acidophilic microorganisms have mechanisms to maintain their cellular pH near 7.2 while living in acidic environments.

Biomineralization (bacterial): the process by which bacteria produce mineral phases. Bacteria are known to form a variety of minerals, both inside and outside the cell. Biomineralization has applications in nanotechnology, wastewater treatment, bioremediation, and metal recovery.

Biohydrometallurgy: a subdivision of hydrometallurgy. Microorganisms are used to produce the leaching agents (oxidants and/or acids) needed for extraction of metals from low-grade ores, tailings, or end-of-use wastes. Biohydrometallurgical methods require lower operating costs, have reduced environmental impact, and can make use of lower-grade ores or wastes – they are hence environmentally sustainable.

Bioleaching: the solubilization of metal(s) from sulfidic ores or solid wastes into aqueous solutions using living microorganisms. The process is applied at a commercial scale to extract base metals (e.g., Cu, Co, and Ni).

Biomining: refers to technologies that utilize microorganisms (e.g., *At. ferrooxidans*, *At. thiooxidans*) to extract and recover metals from ores and waste concentrates. This technology has been applied at industrial scale for processing sulfidic and uranium ores. Use of microorganisms in the extraction of metals from oxidized ores (e.g., laterites) and wastes under oxygen-limited growth conditions is also possible, so far mainly performed at laboratory scale and yet to be applied at the industrial scale.

Biooxidation: the extraction of metals, mainly gold from ores, by oxidizing the matrix in which the metals are embedded. Basically, the metals are made accessible for extraction in this process. Biooxidation is used to release gold in large-scale stirred tanks for further processing.