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Biomining – biotechnologies for extracting and recovering metals from ores and waste materials

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The abilities of acidophilic chemolithotrophic bacteria and archaea to accelerate the oxidative dissolution of sulfide minerals have been harnessed in the development and application of a biotechnology for extracting metals from sulfidic ores and concentrates. Biomining is currently used primarily to leach copper sulfides and as an oxidative pretreatment for refractory gold ores, though it is also used to recover other base metals, such as cobalt, nickel and zinc. Recent developments have included using acidophiles to process electronic wastes, to extract metals from oxidized ores, and to selectively recover metals from process waters and waste streams. This review describes the microorganisms and mechanisms involved in commercial biomining operations, how the technology has developed over the past 50 years, and discusses the challenges and opportunities for mineral biotechnologies in the 21st century.

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Current Opinion in Biotechnology 2014, 30:24–31

This review comes from a themed issue on **Chemical biotechnology**

Edited by **Curt R Fischer** and **Steffen Schaffer**

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<http://dx.doi.org/10.1016/j.copbio.2014.04.008>

Introduction

Biomining is the generic term used to describe technologies that utilize biological systems (chiefly prokaryotic microorganisms) to facilitate the extraction and recovery of metals from ores and waste materials [1^{••},2–9]. Occasionally the term is used synonymously with bio-leaching, though strictly the latter refers to situations where the target metal(s) is solubilized during bio-processing. In some other cases, for example, biomining gold and some other precious metals, microorganisms are used to remove minerals that occlude target metals which are solubilized in a second process (e.g. by extracting with cyanide or thiosulfate in the case of gold; [3]). In such cases, the biological pretreatment stage is referred to as biooxidation. However, both bioleaching and biooxidation, as applied to mineral ores and concentrates, operate

using essentially the same principles and similar consortia of microorganisms. An estimated 15% of copper, 5% of gold and smaller amounts of other metals (such as nickel and zinc) are currently produced globally using biomining technology [1^{••}]. Targeted biomineralization is also used in some active and abandoned mine sites to recover metals from process waters and waste streams [10[•]]

Why biomine?

Bio-extractive techniques have to compete with alternative approaches for extracting metals from ores and concentrates. Some, such as pyrometallurgical technologies (ore roasting/smelting) have been refined over millennia and often represent major investments by mining companies, while others, such as pressure leaching, are more recent non-biological innovations [11]. The main detractions of biomining are the protracted time required to obtain economic levels of metal extraction (which ranges from days, in the case of stirred tanks, to one or more years in the case of bio-heaps and waste rock dumps), and concerns, often unfounded, about the robustness and reliabilities of the biological systems involved. On the other hand, biomining is generally perceived as a much more environmentally benign ('green') approach, involving much lower temperatures (and hence energy costs) and smaller carbon footprints. The latter assertion is justified in that the main microorganisms involved in mineral oxidation processes are autotrophs (i.e. they fix carbon dioxide, much in the same way as green plants), which contrasts with smelting operations that emit large amounts of CO₂. Bioprocessing also operates at atmospheric pressure and at relatively low temperatures (~20–80 °C). No external heat source is usually required as the oxidation of sulfide minerals is an exothermal process. Indeed, excess heat is generated where rates of oxidation are intense (as in stirred tank operations) and systems require to be cooled to maintain suitable temperatures for the mineral-degrading microorganisms (generally 40–45 °C in these systems [3,4]). However, current biomining operations still rely on the blasting and grinding of ore bodies, which is thought to consume ~5% of total global energy production. Bioprocessing also has niche advantages where firstly, the ore or concentrate contains significant quantities of arsenic (which is released in gaseous emissions during smelting but retained in liquid and solid phases in (bio)hydrometallurgical processing) and secondly, for processing low-grade and complex (polymetallic) ores [6,7]. Biomining also allows metal by-products (such as silver) to be more readily recovered from processed ores than is the case with waste slags generated by pyrometallurgy.

Development and evolution of biomining technologies

The first recognized biomining operation was set up within 20 years of the discovery of the first species of bacterium that was demonstrated to catalyze the dissolution of pyrite and other base metal-containing sulfide minerals in acidic liquors [12,13]. In reality, the same biological process had been unknowingly used to extract metals at mine sites in, for example, Spain, the UK and China, for several hundred years [2,5,14], using *in situ* bioleaching (described below). The 'new' biotechnology was established in the 1960s by the Kennecott Copper Corporation to extract copper from waste rock dumps at the Bingham Canyon mine in Utah, and later at the Chino mine in New Mexico [4,15]. The bacterium, *Thiobacillus* (now *Acidithiobacillus*) *ferrooxidans*, and the related species *At. ferridurans* and *At. ferroarans*, grow autotrophically by oxidizing ferrous iron, elemental sulfur and various reduced forms of sulfur, or (most strains) hydrogen [16]. The abilities of the iron-oxidizing acidithiobacilli to generate both ferric iron (the main oxidant of sulfide minerals) and sulfuric acid creates an environment in which they thrive (*Acidithiobacillus* spp. are obligate acidophiles) and accelerate mineral dissolution. Also, and of particular importance in bioleaching, the extreme acidity causes most of the metals released from the degraded sulfide minerals to be retained in solution. These first operations, which have been replicated in many other 'dump leaching' operations (e.g. [17]), involved stacking waste (run-of-mine) rock into huge mounds (often >100 m high) and irrigating with dilute sulfuric acid to stimulate indigenous mineral-oxidizing bacteria (direct inoculation is not used in most dump leaching operations). The copper-enriched liquors that percolate through and drain the dumps (pregnant leach solutions; PLS) are collected in ponds and, in many operations, the copper recovered via cementation (addition of scrap iron to induce an electrochemical interaction with the Cu^{2+} , which results in the precipitation of zero-valent copper). Heap bioleaching later developed as a more refined and intensive irrigation-based biomining option [2,4,5]. In this case, ores is often ground to a finer grain size (which may then be agglomerated), the mounds (heaps) are generally 2–10 m in height (though they can exceed the size of dumps in total volume, such as at the Escondida copper mine in Chile), the heaps are aerated (to provide both oxygen and carbon dioxide for the bioleaching microorganisms) as well as irrigated, and also frequently inoculated with acidophilic microorganisms (Figure 1). The heaps are usually stacked on impermeable membranes to avoid loss of PLS to the underlying ground, and these may in turn be stacked upon each other, to give several 'lifts'. Techniques such as solvent extraction coupled to electrowinning (SX-EW), rather than cementation, are often used to recover target metals. Although again developed initially for copper, bio-heaps have been adapted to process polymetallic ores (e.g. at the Talvivaara mine

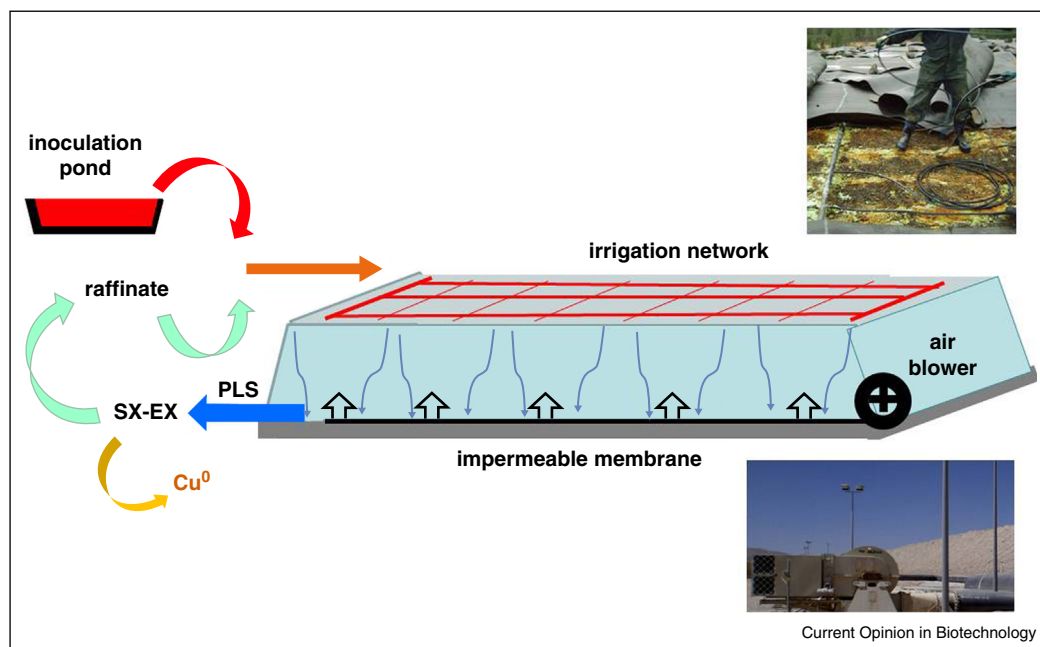
in Finland, where nickel is the primary target metal [18*]) and also as a pretreatment for refractory gold (by the Newmont Mining Corporation [7,19]). Elsewhere, the Geocoat[®] process, in which mineral concentrates are coated onto rock particle supports and then stacked as thin-layer heaps, has been demonstrated to promote more rapid recovery of base and precious metals than conventional bio-heap leaching [20].

Two other engineering designs are used in biomining operations. Stirred tank bioreactors are used almost exclusively for bio-oxidation of refractory gold concentrates (due to their relatively high costs) in which the fine gold particles are enshrouded by sulfide minerals (mainly arsenopyrite and pyrite [2]). Individual mineral bio-processing tanks can have volumes of >1300 m³, making them the largest units used for any biotechnological process. Most current commercial operations use the BIOX[®] process [21] and operate as continuous feed systems, processing between 40 and >8000 tons of concentrate/day [1**]. The first to be commissioned, in 1986, at the Fairview mine in Barberton, South Africa, was still operating in 2013. Stirred tanks were also used to bioleach cobalt from copper mine tailings at the Kasese mine in Uganda from 2000 to 2014 [22] and effective bio-processing of a chalcopyrite concentrate has been demonstrated in a high temperature (~80 °C) pilot-scale stirred tank in Chile [23]. *In situ* mining was used extensively in Canada in the 1970s to recover uranium from worked out deep mines [24]. The residual ore bodies were fractured by controlled underground explosions, the mines flooded, and the uranium-enriched liquors generated pumped to the surface to extract the metal. At one mine alone (the Denison mine) an estimated 300 t of additional uranium was extracted after the main phase of mining using *in situ* bioleaching [2]. A similar approach of recovering metals from deliberately flooding underground mines had previously been used since mediaeval times, long before the realization that microorganisms had a key role in solubilizing sulfide minerals. Intriguingly, *in situ* mineral bio-processing may well be the next major development in the mining sector [25] as the need to utilize deep-buried ore bodies while at the same time minimizing energy costs and carbon footprints could well involve extracting metals from fractured geological strata using microbiologically generated leach liquors (Figure 2).

Mechanisms of sulfide mineral oxidation

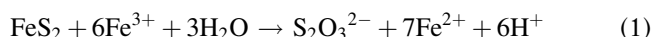
The mechanisms by which sulfide minerals are degraded in acidic liquors by the process of oxidative dissolution has been the subject of a large body of research [26–28], though much of the current consensus derives from the work of Sand, Schippers and co-workers [29,30,31**]. The latter categorized sulfide minerals as either 'acid-insoluble' (e.g. pyrite (FeS_2) and molybdenite (MoS_2)) or 'acid-soluble' (e.g. pyrrhotite (Fe_7S_8), sphalerite (ZnS) and chalcopyrite (CuFeS_2)). The major oxidant of both groups

Figure 1

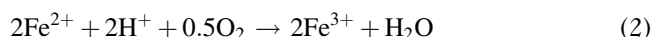


Schematic representation of a biomining heap for leaching low-grade copper ore. The heap is constructed on an impermeable membrane, aerated from below and irrigated from above. Microbial activity within the heap accelerates the oxidative dissolution of copper minerals such as chalcocite (Cu_2S). Copper may be removed from the pregnant leach solution (PLS) using solvent extraction and electrowinning, producing pure grade cathode-copper. The copper-depleted raffinate solution is recirculated through the heap via a network of pipes laid out on the heap surface, which are usually covered with a waterproof thermal cover to conserve moisture and heat. The recirculating liquor may be combined with water from an inoculating pond in which mineral-degrading acidophiles have been grown to $\sim 10^9$ cells/ml. The inset photographs show the installation of an irrigation system and thermal cover (top) and an air blower fan (bottom) at two different mine sites.

is ferric iron although, as implied, minerals in the second category can also be degraded by hydronium ions. Ferric iron attack on acid-insoluble minerals oxidizes the sulfur moiety in the mineral to a sulfur oxyanion (the 'thiosulfate pathway'; e.g. (1)):

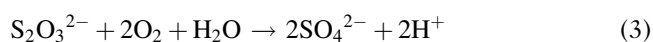


Although oxygen is not directly involved in this reaction, the regeneration of ferric iron (a *sine qua non* of conventional biomining operations) does require oxygen (Eq. (2)):

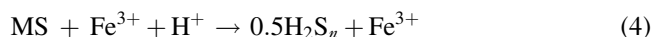


Also, since the abiotic oxidation of ferrous iron is very slow in acidic, low temperature ($<60^\circ\text{C}$) liquors [32], iron-oxidizing acidophiles are also necessary for continuation of the process.

Thiosulfate is highly unstable in bioleach liquors and is rapidly oxidized to sulfuric acid, either abiotically, by ferric iron (which does not require oxygen) or by sulfur-oxidizing acidophiles, which can couple the oxidation of thiosulfate either to the reduction of ferric iron or oxygen (Eq. (3)):

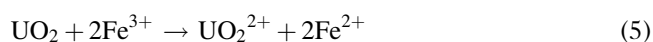


With acid soluble sulfides ('MS'), the sulfide moiety is oxidized to elemental sulfur, via a variety of polysulfides (designated as H_2S_n , in Eq. (4), where $n \geq 2$) in the 'polysulfide pathway' [29,31**]:



Oxidation of the polysulfides to elemental sulfur is mediated by ferric iron. Sulfur may accumulate as free aggregates and crystals or as a layer around the oxidizing sulfide mineral [31**] or be oxidized further by sulfur-oxidizing acidophiles under both aerobic and anaerobic conditions [33].

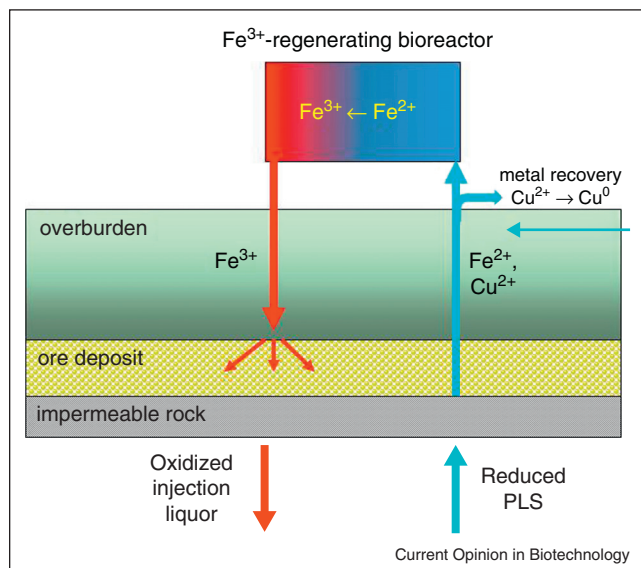
In the case of uranium biomining [24], the situation is somewhat different. This metal does not form a sulfide phase, but occurs as the mineral uraninite (UO_2) which is often in association with pyrite deposits. Ferric iron generated by biologically catalyzed oxidative dissolution of iron sulfides oxidizes insoluble U(IV) to soluble U(VI) (Eq. (5)) which can then be recovered by ion-exchange:



The microbiology of biomining

The extreme physico-chemical nature of bioleach liquors — low pH, elevated concentrations of (toxic)

Figure 2



Projected set up for *in situ* biomining of a deep-buried copper ore body. An acidic ferric iron-rich liquor is injected through a borehole into the fractured ore body, where it oxidizes the copper sulfide minerals. The copper-rich and ferrous iron-rich liquor is pumped to the surface, the copper removed (e.g. using SX-EW) and the ferric iron leach liquor regenerated in a bioreactor housing acidophilic iron-oxidizing prokaryotes.

metals, metalloids and other solutes, and highly positive redox potential (E_H values may exceed +900 mV) — means that they are highly toxic to the vast majority of life forms, including microorganisms. All biomining operations work necessarily under non-sterile conditions which preclude or restrict the use of genetically engineered microorganisms, even if they were demonstrated to be superior to non-engineered strains. Although pure cultures of bacteria or archaea can degrade sulfide minerals, it is now well established that bioleaching and biooxidation in all biomining operations is mediated by consortia of acidophilic prokaryotes [34]. These have been categorized as: firstly, ferric iron-generating autotrophs (primary prokaryotes) which produce the mineral oxidant; secondly, sulfuric acid-generating autotrophs (secondary prokaryotes), which maintain the low pH environment required; and finally, heterotrophic and mixotrophic (tertiary) prokaryotes, which degrade organic compounds leaked from autotrophic iron-oxidizers and sulfur-oxidizers, thereby avoiding potential toxicity issues. There is considerable overlap between these groups, however, as some autotrophs can oxidize both iron and sulfur while some heterotrophic/mixotrophic species can also oxidize iron or sulfur (or both [16]). Acidophilic mineral-degrading prokaryotes vary greatly in the range and optimum temperature at which they grow, which means that biomining can operate over a wide temperature spectrum [35,36,37].

Although *At. ferrooxidans* was the first, and remains the most well-known and widely studied, biomining microorganism [12], it is by no means unique in its ability to degrade sulfide minerals. Many different species of bacteria and archaea are now known to catalyze ferrous iron oxidation at low pH and, while all of these would, in theory, be expected to oxidize sulfide minerals (via the ferric iron), other factors, such as sensitivities to extremely low pH or to elevated concentrations of some metals and metalloids found in mineral leachates, means that some (such as '*Ferroplasma myxofaciens*', an iron-oxidizing acidophile common in many acid mine drainage waters) are rarely, if ever encountered in a biomining context [34]. Those acidophilic prokaryotes that have been identified in biomining environments are listed in Table 1.

Controlled pH (~1.5–1.8) and temperatures (typically 40–45 °C) in stirred tank systems, coupled with the fact that high throughput rates select for fast-growing strains, restricts the diversity of indigenous microflora to about 3–6 moderately thermophilic species. *Leptospirillum ferriphilum* is often the dominant (or exclusive) iron-oxidizing autotroph, and *Acidithiobacillus caldus* the dominant sulfur-oxidizing autotroph in stirred tank operations. Degradation of organic carbon is mediated by iron/sulfur-oxidizing *Sulfobacillus* spp. (facultative autotrophs) and/or by iron-oxidizing euryarchaeotes (*Ferroplasma* or *Acidiplasma* spp.; obligate heterotrophs). The composition of the microbial community can change radically in stirred tanks configured sequentially, with heterotrophic iron-oxidizing euryarchaeotes being more prominent in downstream tanks (often as a result of mass mortality of chemoautotrophic bacteria [38,39]). There is also evidence that many BIOX[®] stirred tanks operated in different geographical locations are becoming increasingly dominated by *Ferroplasma*/*Acidiplasma*-like archaea [40].

Irrigated biomining operations (dumps and heaps) present, from a microbial perspective, very different challenges and opportunities to stirred tanks. These are characterized by spatial and temporal heterogeneity of key physico-chemical parameters such as pH, temperature and leachate chemistry. Consequently the microbial biodiversity of biomining heaps (which have been far more intensively studied than dumps) is known to be far greater than that of stirred tanks, and can also change greatly as heaps evolve. Indigenous prokaryotes may, for example, become increasingly supplanted by introduced microflora in situations where heaps are inoculated [41]. Also in contrast to stirred tanks, the ability of microorganisms to attach to minerals is an important attribute in irrigated systems, to prevent their washout in percolating leach liquors. Many biomining microorganisms are adept at generating extracellular polymeric substances (EPS) by which they attach to surfaces and develop biofilms [31,42], though the propensity for EPS production and attachment varies greatly between species of acidophilic bacteria, and even between strains of

Table 1

Acidophilic bacteria and archaea identified in biomining operations

Species	Temperature characteristics ^a	Notes
Bacteria		
<i>Acidithiobacillus</i> (<i>At.</i>) <i>ferrooxidans</i> / <i>ferridurans</i> / <i>ferrivorans</i>	M ^b	Oxidize Fe ²⁺ /S and reduce Fe ³⁺
<i>At. caldus</i>	MT	Dominant S-oxidizer in stirred tanks
<i>At. thiooxidans</i>	M	S-oxidizing autotroph
<i>Acidiferrobacter thiooxydans</i>	M/MT	Oxidizes Fe ²⁺ /S and reduces Fe ³⁺
<i>Leptospirillum</i> (<i>L.</i>) <i>ferriphilum</i>	MT	Dominant Fe ²⁺ -oxidizing autotroph in stirred tanks
<i>L. ferrooxidans</i>	M	Fe ²⁺ -oxidizing autotroph
<i>Sulfobacillus</i> (<i>Sb.</i>) <i>thermosulfidooxidans</i>	MT	Oxidizes Fe ²⁺ /S and reduces Fe ³⁺
<i>Sb. benefaciens</i>	MT	Isolated from stirred tanks leaching Co-pyrite
<i>Sb. thermotolerans</i>	MT	Oxidizes Fe ²⁺ & S
<i>Alicyclobacillus</i> spp.	MT	Some species can oxidize Fe ²⁺ & S
<i>Acidiphilium</i> spp.	M	Most strains/species are obligate heterotrophs; all reduce Fe ³⁺
<i>Acidimicrobium ferrooxidans</i>	MT	'Heterotrophically inclined' Fe ²⁺ -oxidizer
<i>Ferrimicrobium acidiphilum</i>	M	Obligately heterotrophic Fe ²⁺ -oxidizer
Archaea		
<i>Ferroplasma acidiphilum</i>	M/MT	Heterotrophic Fe ²⁺ -oxidizer
<i>Acidiplasma cupricumulans</i>	MT	Heterotrophic Fe ²⁺ -oxidizer
<i>Sulfolobus</i> (<i>S.</i>) <i>metallicus</i>	T	Autotrophic Fe ²⁺ /S-oxidizer
<i>S. shibatae</i> -like	T	Facultative chemolithotroph (oxidizes S)
<i>Metallosphaera</i> spp.	T	Facultative autotrophs; obligate aerobes
<i>Acidianus</i> (<i>Ac.</i>) <i>brierleyi</i>	T	Catalyzes the oxido-reduction of S, and oxidation of Fe ²⁺
<i>Ac. sulfidivorans</i>	T	Reported to grow at pH 0.35 and 83 °C
<i>Ac. infernus</i> -like	T	Catalyzes the oxido-reduction of S
<i>Sulfurisphaera ohwakuensis</i> -like	T	Similar characteristics to <i>Acidianus</i> spp.
<i>Stygiolobus azoricus</i> -like	T	Obligate anaerobe; grows by S respiration

^a M, mesophilic (optimum 20–40 °C); MT, moderately thermophilic (optimum 40–60 °C); T, thermophilic (optimum >60 °C).

^b Strains of *At. ferrivorans* are cold-tolerant.

a single species [43]. Most analyses of microbial populations in biomined dumps and heaps have been carried out using leachates, and the compositions of communities that are attached to the mineral phases are less well known [44].

The projected development of *in situ* mining of deep buried ores will provide new challenges. Delivering oxygen and carbon dioxide to promote microbial growth and activity within a deep-buried, fractured ore body could be highly problematic, and an alternative approach might be to use an 'indirect' bioleaching protocol, in which a ferric iron-rich leach liquor (generated in a bioreactor located at the mine surface is injected into the ore body (to mediate reactions such as that in Eq. (1)). (generated in a bioreactor located at the mine surface) is injected into the ore body, to mediate reactions such as that in Eq.(1). The metal-laden ferrous iron-containing PLS is then pumped to the surface for metal extraction and regeneration (Figure 2). This cycle would continue until the *in situ* ore body is mostly depleted of target metals.

It has been suggested that genetic manipulation of biomining prokaryotes could produce strains that would be more effective than native strains in situations where the latter are stressed, such as when saline irrigation solutions are used in heap and dump operations. However, the

engineering constraints of all forms of biomining operations (including stirred tanks) means that it is not possible to prevent the release of microorganisms used in these processes to the environment. Consequently, the issue of genetic manipulation has received far less attention in biomining than in many other areas of biotechnology.

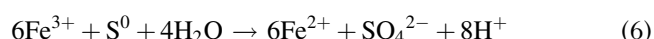
Some recent developments in biomining technologies

Metallic wastes/*urban biomining*: Bioleaching has been tested as a potential method to solubilize and recycle base and precious metals from electronic waste ('e-waste') materials, such as printed circuit boards (reviewed in [45]). Neutrophilic heterotrophic fungi and bacteria, as well as *Acidithiobacillus* spp. have been used in these tests. Leachates from e-wastes, and other domestic and industrial metallic waste materials, often contain a large number of different soluble metals, and a major challenge is how to recover these metals as separate entities, for example using selective biomineralization or non-biological separation technologies.

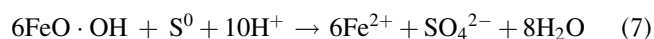
Bioleaching at low redox potentials: Although copper has been, and continues to be, the most actively biomined metal, chalcopyrite (CuFeS₂; the most abundant of all

copper minerals) and another primary copper sulfide mineral, enargite (Cu_3AsS_4), are both highly recalcitrant to conventional bioleaching [46]. Often only $\sim 20\%$ of copper is extracted from chalcopyrite using conventional bioleaching. The presence of 'passivation' layers that form on the mineral surface during (bio)leaching is usually cited as the cause, though what constitutes these layers (elemental sulfur, polysulfides and jarosites) has been keenly debated. High temperature ($70\text{--}80\text{ }^\circ\text{C}$) bioleaching using thermophilic archaea can circumvent this problem [23] though this has its own endemic problems, such as the highly corroding nature of the leach liquors which preclude the use of stainless steel tanks, and problems with the solubility and exchange of oxygen. An alternative approach is to bioleach at lower temperatures but also at controlled and less positive redox potentials, for example, by controlling air flow rates [47,48]. Gericke *et al.* [49], for example, showed that 97% of copper could be bioleached from a chalcopyrite concentrate at a E_{H} of $\sim +630\text{ mV}$ compared to 64% at an E_{H} of $\sim +900\text{ mV}$, in pilot-scale bioreactors maintained at $45\text{ }^\circ\text{C}$.

Bioreductive dissolution of minerals: Using bacteria to catalyze the reductive dissolution of minerals has been developed to extract target metals from oxidized ores and deposits, such as lateritic materials. This makes the process distinct from both conventional biomining practice and low redox techniques, which both target sulfidic ores. Another major difference is that bioreductive mineral dissolution operates under anoxic conditions. However, some species of acidophilic bacteria that catalyze the oxidative dissolution of sulfides can also be used to reduce and solubilize oxidized (iron (III) and manganese (IV)) minerals. These include the iron-oxidizing acidithiobacilli (*At. ferrooxidans*, *At. ferridurans* and *At. ferrivorans*) that couple the oxidation of sulfur to the reduction of ferric when oxygen is absent (Eq. (6)):



One potential application is to bioleach nickel from limonitic deposits, which account for most of this metal in surface deposits. These deposits may contain $\sim 0.5\%$ Ni, most of which is intimately associated with the ferric iron minerals such as goethite ($\text{FeO}\cdot\text{OH}$), a mineral that is susceptible to bioreductive dissolution at low pH, though this reaction consumes rather than generates protons (Eq. (7)):



Around 80% of nickel present in a limonitic deposit was solubilized using solubilized at $30\text{ }^\circ\text{C}$ by *At. ferrooxidans* using reductive bio-processing approach [50]. The Mn(IV) mineral asbolane was solubilized concurrently, releasing associated cobalt, and chromium released (by acid dissolution of chromite (FeCr_2O_4) also present in the limonite) was retained in the +3 oxidation state rather than oxidized to the far more toxic +6 oxidation state [51]. This approach appears to have generic application

for oxidized metal ores, and an integrated process (the *Ferredox* process) for bio-processing metal-rich limonitic deposits has been described [52].

A different bioreductive process has been proposed for removing elemental sulfur produced during the ultra-fine grinding of enargite (a pretreatment to recover associated gold [53]). In this, a mixed culture of anaerobic sulfur-reducing and sulfate-reducing bacteria was used to reduce the sulfur produced by grinding the ore, to hydrogen sulfide. This resulted in an increase in the amount of gold recovered from 49% with no bioreduction stage, to 70%, though whether this process was superior to one where the sulfur was oxidized rather than reduced was not ascertained.

Conclusions

Biomining is well established as a niche technology for extracting metals from low-grade and polymetallic base metal ores, and refractory gold ores. As energy and environmental constraints become more demanding, there will be greater need and incentives to reprocess relic mine wastes (which often contain greater concentrations of metals than readily accessible ore bodies) and to recover and recycle metals from electronic and other metallic wastes and metal-laden waste waters, while *in situ* biomining could allow deeply buried ore bodies to be economically exploited. Although a number of unresolved challenges in conventional biomining remain, such as bioleaching chalcopyrite and using brackish and saline water for bio-processing minerals, recent innovations, such as the reductive bio-processing of oxidized metal deposits, suggest that new opportunities for developing biotechnologies in the mining and mineral sectors will emerge in the near future.

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- of special interest
- of outstanding interest

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