Chapter 1
Evolution and Current Status of Mineral Bioprocessing Technologies

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Abstract Metals have been used for thousands of years and have had pivotal roles in the development of human civilisation. Both the scale and range of metals that are used in modern and emerging technologies, and industrial and domestic applications have increased vastly in recent years. Harnessing microorganisms to facilitate the extraction and recovery of metals from mineral ores and waste materials has been often promulgated as a more environmentally benign approach than conventional methods, such as pyrometallurgy, yet "biomining" remains a niche technology, used primarily to bioleach copper ores and biooxidise refractory gold ores. This chapter charts the development of mineral bioprocessing technologies since the discovery of the first bacteria that were shown to accelerate the dissolution of sulfide minerals, and highlights their perceived strengths and weaknesses. The diverse engineering approaches used in biomining, and the role of microbial consortia in liberating metals from sulfide ores, are highlighted.

Keywords Acidophiles · Biomining · Bioheaps · Bioleaching · Biooxidation · Microbial consortia · Stirred tank bioreactors

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1.1 Metals, Minerals, and Human Civilisation: The Context and Early History of Biomining

Humans have a long and sometimes fraught relationship with metals and metal mining. Major changes in progression of civilisations have, in the past, been driven by our ancestors discovering how to obtain and use “new” metals and alloys. The transformation of civilisations from Neolithic (New Stone Age) to the Bronze Age (the first period of the “Metal Age”) is estimated to date from about 4300 years BP in Indo-Europe. This was underpinned by the discovery and production of copper–tin alloy, which had many superior properties to the two metals individually, and was accompanied by major social and technological advances. Archaeological evidence for bronze age mining of copper and tin is widespread, stretching from the southeast (e.g., Cyprus) to the northwest (e.g., Wales) of Europe. The following era in human civilisation, the iron age, estimated to extend from ca. 2800 to 1900 years BP was defined by metalworking being dominated by ferrous metallurgy. Since iron is harder and more abundant than copper and tin, this became the metal of choice for many applications. The method used then (and mostly today) to obtain metals involved roasting with materials such as charcoal to provide the reductant for reducing the metal to zero-valent iron. As in modern times, metal mining in pre-antiquity would have doubtless provided opportunities for microorganisms to colonise exposed ore bodies and degrade minerals. There is, however, at least one reference from the Renaissance period to what appear to be bioleach liquors in *De re metallica* (“On the nature of metals”) a text written in Latin by Georg Bauer (Georgius Agricola) in 1556. In western Europe, China and probably elsewhere in the middle ages, miners learned that, by periodically allowing the deeper mines and adits to flood and then draining the waters into lagoons and ponds, it was possible to obtain crude copper without roasting the ore bodies. This was done by adding scrap iron, which dissolved concurrent with the appearance of “cement copper”, a phenomenon that was perceived as alchemy (the transformation of one metal into another). Interestingly, this approach for extracting copper (in situ (bio)mining) and its electrochemical recovery has persisted well into the modern era of biomining.

While *Homo sapiens* has been exploiting metal ores for thousands of years, this is dwarfed by the millions of years since prokaryotic microorganisms first developed intimate associations with metal-containing (and other) minerals. The first primitive single-celled life forms are thought to have emerged relatively soon (ca. 4000 million years ago; Mya) after the planet coalesced (ca. 4600 Mya). There is considerable debate about what forms of energy (electron donors) and electron acceptors were used by primitive prokaryotes, though it seems highly probable that inorganic materials are prime candidates for both roles. This may be observed today with some acidophilic archaea and bacteria that can colonise biomining environments, e.g., *Acidianus* spp. that couple oxidation of hydrogen to the reduction of sulfur. The “great oxidation event”, which caused the anoxic planet to become transformed with an oxygen-enriched atmosphere, and which is thought to have initiated somewhere between 2000 and 2400 million years Mya, would have been a major game changer for bacteria and archaea, allowing them to access, indirectly, the energy released by transforming sulfide minerals such as pyrite (FeS_2) using molecular oxygen as an electron acceptor. This is essentially the same fundamental microbial metabolism that is harnessed in all current full-scale biomining operations.

There are two major differences between historic and modern-day mining of metals and how they are used. One is in scale. It has been estimated that humans have mined as much metal from the lithosphere in the past 30 years as in all previous times combined, with ore grades steadily decreasing, and consequently more waste produced. Second, the range of metals required for modern applications, technologies, and consumables, is far greater than in the past, and includes a number of rare earth as well as transition metals. The demand for some metals which had only minor use in past times (e.g., cobalt, which had been used primarily as a pigment) has dramatically escalated in more recent times, causing their commodity prices to rocket and increasing effort to find and exploit new sources, both primary ores and waste materials. The list of critical raw materials compiled by the European Union, the majority of which are metals, increased from 14 in 2011 to 30 in 2020. The current trend in switching from fossil fuel-driven to electric vehicles, and in generating energy from renewable sources, will doubtless result in major increases in demand for metals in general and for those used for generating and storing electric energy, in particular, in the twenty-first century. The question of whether accessible reserves of many of these metals are adequate for meeting the projected demands is something that has not always been considered sufficiently.

1.2 The Modern Era: Development and Application of Engineering Designs of Full-Scale Biomining Operations

The modern era of commercial-scale mineral bioleaching (i.e., post Antonie van Leeuwenhoek, who is credited with the discovery of bacteria in 1676) began within 20 years of the isolation of a bacterium (then named as *Thiobacillus ferrooxidans*) from an acidic ferruginous coal mine drainage stream in West Virginia. Since then, understanding how microorganisms can liberate or make accessible metals in sulfidic ore bodies, their diversities and interactions, and the engineering design options that can be used for bioprocessing sulfidic ores and concentrates has expanded greatly. A number of review articles have been written on this topic in scientific journals and books, including Brierley (2008a, b), Brierley and Brierley (2001, 2013), Rawlings (1997, 2002, 2005), Rawlings and Silver (1995), Rawlings et al. (2003), Rawlings and Johnson (2007a), Johnson (2010, 2013, 2014, 2018). In addition, proceedings published from the biennial International Biohydrometallurgy Symposia and Biohydrometallurgy/Biomining conferences are a major repository and resource of information on mineral bioprocessing from fundamental studies to full-scale operations.

Dump leaching was the initial design used for engineering a biomining operation, with the first full-scale system established by the (then) Kennecott Copper Corporation at the Bingham Canyon mine in Utah, and shortly afterwards at the Chino mine in New Mexico. Dump leaching has since been applied in many other countries and is used still to extract, primarily, copper from low grade (<0.1–0.5%) waste rock and run-of-mine-ore. Ungraded material, comprising fine dust particles to large boulders, are stacked in mounds that may exceed 100 m in height, and irrigated with sulfuric acid to stimulate the activities of indigenous acidophilic prokaryotes that degrade the copper sulfide minerals present. The copper-enriched leachates (pregnant leach solutions; PLS) are channelled into vats and copper is recovered, often using cementation as described above. The process is slow and individual dumps may be used over several years or even decades. Although it uses relatively crude engineering and little or no control of microbiology, dump leaching continues to be a major contributor to global copper production. Heap leaching, which has its origins in Chile, Australia, and elsewhere in the 1970s, uses a similar general approach, but with greater refinement and capital investment. Again, heap leaching is used largely to extract copper, though bioheaps have also been used as a pre-treatment for extracting gold from refractory ores, and more recently for processing polymetallic ores. The main upgrades used in heap compared with dump biomining are: (1) ores are usually crushed and graded, and sometimes also agglomerated; (2) materials are transferred to pads that have impermeable high-density plastic liners and pipe networks to collect and transfer PLS, and the heaps are ideally constructed by conveyor stacking rather than truck dumping; (3) heaps are actively aerated to provide the mineral-degrading microorganisms with not only a supply of oxygen, which is required for the oxidative dissolution of sulfide minerals, but also carbon dioxide, as the principal prokaryotes involved are, like green plants, autotrophic; (4) heaps are often inoculated to ensure their exposure to suitable biomining microflora (which may need to include those that operate over very different temperature ranges to cope with those often found in heterogeneous heaps); (5) target metals in PLS are often extracted using solvents (followed by electrowinning to produce high-grade cathodic metals) and the raffinate liquors generated pumped back into the heap circuit (with or without an additional inoculum) using an irrigation network placed on the heap surface, sometimes below a plastic cover that serves both to act as a thermo-insulator and, depending on climatic factors, reduce moisture loss by evaporation or inputs of meteoric water. The life of heaps is typically 1–2 years, after which they can be removed and treated to minimise the ongoing dissolution of remaining reactive minerals. Alternatively, heaps can be stacked progressively upon each other, ultimately forming a large multilayered structure, such as at the Escondida mine in Chile. A modified approach for heap leaching involves agglomerating fine-grain mineral concentrate particles onto coarser rock fragments and regenerating the carrier material once the former have been oxidised. The Geocoat® process (Harvey and Bath 2007) was claimed to reduce the processing time in a bioheap to about 2 months.

A radically different operational design for mineral bioprocessing was initiated in the 1980s in South Africa and has since seen plants established in many countries in different parts of the world. Continuous-flow stirred tank reactors are used primarily to biooxidise refractory gold concentrates but have also been used to bioleach cobalt and nickel from mineral wastes. Large (>1000 m^3) tanks constructed from corrosion-resistant stainless steel and fitted with pipework to facilitate the flows of liquids and air, one or more impeller connected to a motor to maintain fine-grain particles in the mineral slurries in suspension, and a cooling system (the accelerated rate of mineral oxidation compared to dumps and heaps generates a lot of heat) are used either as single units or in series, through which the slurries are transferred. Target metals are recovered from the solution phase in the case of bioleaching, or from the partially processed biooxidised mineral phase by chemical extraction in the case of gold. Stirred-tank bioprocessing is much more rapid than dump and heap operations, typically requiring only 3–6 days to be complete.

A number of worked out uranium mines in Canada were subjected to an end-of-life bioleaching phase (in-place, or in situ, leaching) in the 1970s and 1980s. Controlled blasting was used to fracture the residual buried ore bodies and the collapsed underground structures were allowed to flood. Soluble uranium (VI) was extracted from the acidic leach liquors produced from the solubilised uranite (UO_2), accounting for about 300 t in one mine (the Denison mine) during 1 year of in-place leaching. This was essentially a refined application of the mediaeval practice of in situ bioleaching described above. A development of this approach (deep in situ biomining) wherein ore bodies present deep in the lithosphere are processed without the need for haulage and comminution, is currently being evaluated for its economic viability and acceptance by society as an alternative strategy for mining metals in the twenty-first century (Chap. 17).

Some milestones in the development of biomining engineering and operational designs are given in Table 1.1, and images from some of these are in Fig. 1.1.

1.3 The Biomining Niche: Limitations and Opportunities

In the late twentieth century, by which time biomining had become an established and expanding biotechnology with operations in place in various parts of the world, there was great optimism shared by many researchers working in the field that it would have major, and even revolutionary, impact on the metal mining sector. In reality, however, its impact and uptake have been far more limited. While bioprocessing of metal ores has been estimated to account for between 10 and 20% of global copper production, ~1% of gold, and smaller amounts of other base metals, such as cobalt and nickel, it remains, in essence, a niche technology. There are a number of reasons for this.

Biomining is frequently claimed by its protagonists to be a "green technology" but the actual case for this is not always that strong. While many of the bacteria and archaea involved in biomining operations are autotrophic (i.e., fix CO_2), their contributions to global carbon budgets are minor. Much of the energy demand and carbon footprint of metal mining is associated with excavating, haulage, and

Table 1.1 Some key milestones in the development of biomining technologies

Year	Event
	Dump operations
1960s	Bioleaching of run-of-mine ore in dumps established at two sites (in Utah and New Mexico) operated by (the then) Kennecott Corporation
1979	Recovery of copper from “waste” rock at the Dexing mine (China)
	Bioheap operations
1980	Copper heap bioleaching established in Chile (Lo Aguirre mine)
1992	Copper bioheap established at Mount Gordon, Australia
1998	First copper heap bioleaching operation in Myanmar (Sabetaung and Kyisintaung mine)
1999	First biooxidation heap leach commissioned for processing refractory gold ore (Newmont Corp)
2003	Commissioning of the first heap biooxidation operation using GEOCOAT® technology Agnes mine, South Africa)
2006	Copper bioleached from stacked bioheaps at Escondida, Chile (the world’s largest copper mine)
2008	Heap bioleaching of a polymetallic (Ni, Zn, Cu) schist established at Talvivaara, Finland
2013	First cathode produced from 1 million tonne commercial-scale enargite bioleach demonstration at Minera Yanacocha, Peru
	Continuous stirred-tank operations
1986	First commercial biooxidation reactor for refractory gold ore (Fairview, South Africa); BIOX® technology
1994	First full-scale operation using BacTech technology to process refractory gold ores (Youanmi, Australia)
1999	Stirred-tank bioleaching of pyritic waste to extract and recover cobalt (Kasese, Uganda)
2003	Large-scale (<8000 t/d) ore treatment of refractory gold concentrate, Olimpiada, Polyus, Russia
2015	Stirred-tank bioleaching of a nickel sulfide concentrate (by-product of talc extraction; Mondo Minerals, Finland)

Referenced from: Olson et al. (2003), Morin and d’Hugues (2007), Brierley (2008b), Wu et al. (2008), Brierley and Brierley (2013), Riekkola-Vanhanen (2013), and Chap. 12. More comprehensive lists of earlier bioheap and stirred-tank bioleaching operations can be found in Watling (2006) and Brierley (2008a).

comminution (rock grinding and sorting), which is often followed by generating mineral concentrates for final processing (Curry et al. 2014). Most stirred-tank operations require all of these up-front processing steps, and it is only the concentrate bioprocessing stage that can justifiably be regarded as relatively “green”. Dump and heap leaching do not require all of the preprocessing stages, while the bioleaching of mineral tailings and other wastes uses materials that have already been subjected to haulage etc., and are therefore among the most environmentally benign applications of biomining. Combined with this, bio- and subsequent processing can generate more secure secondary mineral wastes that could be used for other purposes, fulfilling an objective of a circular economy.

The general area of hydrometallurgy includes biomining technologies, as well as others (e.g., chemical leaching) that do not involve biological systems. The fact that

Fig. 1.1 Images from sites where different approaches are used to bioleach or biooxidise sulfidic ores and concentrates to recover base and precious metals. (**a**) precipitation pond, used to recover copper from in situ bioleaching (Mynydd Parys, Wales); (**b**) run-of-mine and crushed ore bioleach heaps (Yanacocha mine, Peru); (**c**) pond receiving copper-rich pregnant leach solution from a trial heap leach (Bingham Canyon mine, Utah); (**d**) bioleach aeration blowers and distribution plenum (Yanacocha mine, Peru); (**e**) copper cathode produced by SX-EW (Phoenix mine, Nevada); and (**f**) continuous stirred tanks used to process refractory gold ore (Suzdal mine, Kazakhstan)

biotechnologies are regarded by some, and possibly many, in the mining industry as being not sufficiently robust, has impeded their acceptance. Bioprocessing ores and concentrates has to compete with alternative approaches, such as pressure leaching, which are also continuing to make significant technological advances, as well as with pyrometallurgy. Smelters represent major investments for mining companies, with constructing and commissioning a single smelter costing in the order of $1 billion. However, bioprocessing mineral ores and concentrates is invariably much slower than competing technologies, and this is a significant detraction. This latter downside, throughput, is probably the biggest reason bioprocessing is not applied by mining companies on a similar scale to competitor technologies like pressure oxidation. Ultimately, time under leach is a negative for bioleach/whole-ore biooxidation compared to chemical leaching—sulfuric acid (perhaps with ferric iron) for copper, and cyanide for gold.

There are, however, niche areas where biomining can compete with alternative technologies, some of which, such as for processing low-grade/run of mine ores, reprocessing mine wastes, and biooxidising refractory gold ores, have already been touched upon. In some situations, it has not been found possible to produce a high-grade mineral concentrate from an ore (such as the polymetallic ore body at Talvivaara/Terrafame in Finland, which contained ~10% graphite) and bioleaching rather than smelting ground ore was therefore considered to be preferable. The elevated arsenic content of some mineral ores and concentrates can preclude processing in smelters due to legislative restrictions, though companies often blend high and low arsenic-containing materials to get around this barrier. New technology is emerging at the world's only smelter currently taking high-arsenic concentrates (Tsumeb in Namibia) to incorporate up to 20% arsenic (by weight) in glass. Bioprocessing, like other hydrometallurgical approaches, has the advantage that solubilised arsenic is retained in solution rather than emitted in flue gases, and can be precipitated from liquid wastes as a relatively stable mineral (such as scorodite or ferric arsenate) and stored securely.

1.4 The Microbiological Context of Biomining

Biomining environments are typified by being acidic (sometimes extremely so), rich in soluble metals and other solutes, such as sulfate, and having widely varying temperatures. Knowledge of microbial species that contribute to biomining processes and understanding of how these interact both with minerals and with each other has increased markedly since the early days when the sole bacterium thought to have a direct role in accelerating the oxidative dissolution of sulfide minerals was (*Acidi) thiobacilllus ferrooxidans*. Since all current commercial-scale biomining operations operate at low pH, active microbial populations are limited to acidophiles. An account of how this area has expanded since the discovery of the very first acidophile (the sulfur-oxidiser (*Acidi)thiobacillus thiooxidans*, in the early 1920s) can be found in Johnson and Quatrini (2020). Several novel isolates, representative of genera and species that would subsequently be identified as prokaryotes that have widespread and major roles in biomining operations, were described in the 1970s. These include: (1) *Leptospirillum ferrooxidans*, isolated by Markosyan (1972) from a copper mine in Armenia, though its related thermo-tolerant relative *Leptospirillum ferriphilum* is now recognised as having a more important role in commercial biomining operations, and has often been identified as the dominant iron-oxidising bacterium present; (2) the first thermo-acidophilic archaeon (a member of the order Sulfolobales; Brierley and Brierley 1973); (3) the first mixotrophic mineral-oxidising bacterium (the thermo-tolerant Firmicute, *Sulfobacillus*; Golovacheva and Karavaiko 1979). Many new species of acidophilic prokaryotes have since been described, which has been greatly aided by the advent of molecular microbiology techniques. For example, in the past all rod-shaped mesophilic acidophiles that could oxidise both iron and sulfur tended to be classified as strains of *At. ferrooxidans*, the iron-oxidising acidithiobacilli currently comprise five distinct species. Not all acidophilic microorganisms can thrive in bioleach liquors, however, as other factors, particularly elevated concentrations of transition metals, may preclude this.

Probably as important as the isolation and identification of species that can mediate sulfide mineral dissolution was the recognition, particularly over the past 20 years, that these both co-exist with, and interact with other microorganisms both in natural and anthropogenic environments, such as "biomines" (Rawlings and Johnson 2007b). Biomining systems from dumps to stirred tanks all necessarily operate as open, non-sterile environments where microorganisms can be introduced from a number of sources, such as atmospheric deposition or the ore/concentrate itself. Likewise, it is not possible to totally preclude microorganisms in a mine site from migrating to the wider environment, which is why it is unlikely that genetically modified acidophiles will find an application in industrial-scale biomining operations. Although sulfide minerals can be degraded by pure cultures of acidophilic iron-oxidising bacteria such as *Leptospirillum* spp. and some *Acidithiobacillus* spp. in the laboratory, microbial consortia are both more effective and robust, and invariably found in actual biomining operations. While the individual species may differ from site to site, and especially with temperature, the presence of the same three functional groups appears to be universal in dumps, tanks, and heaps. These are: (1) iron-oxidisers, which catalyse the initial oxidative dissolution of sulfide minerals by their continuous regeneration of the oxidant, ferric iron; (2) sulfur-oxidizers, which oxidise sulfur oxyanions and zero-valent sulfur, generating sulfuric acid and thereby maintaining conditions that are conducive both to the iron-oxidisers and also for retaining the cationic metals released from minerals in solution, facilitating their downstream recovery; (3) organic carbon degraders (heterotrophic and mixotrophic acidophiles) that metabolise the soluble organic carbon compounds released from active and moribund/dead iron/sulfur-oxidisers and which may otherwise build up to concentrations that inhibit the latter. Many of the third group can also oxidise iron and/or sulfur, such as *Sulfobacillus* and *Ferroplasma* spp., and some, at least, of the CO_2 they generate is used by bacteria in groups (1) and (2), which are primarily autotrophic.

While the generic composition of microbial consortia required for efficient bioleaching may be essentially the same for all engineering configurations, there are important differences between bioheaps and stirred tanks that have major influences on formulating the compositions of microbial inocula (Rawlings and Johnson 2007b). Bioheaps can be highly heterogeneous in terms of temperature and chemical microenvironments, and major selective pressure on the indigenous microflora is their ability to attach to mineral particles (as biofilms) in the heap to minimise or avoid washout. In contrast, stirred tanks are homogeneous, providing constant conditions for microbial growth though the relatively fast throughput selects for faster-growing consortia. As a consequence, microbial populations in stirred tanks tend to be dominated by relatively few (3–4) species of acidophiles, whereas far greater biodiversity is found in heaps, and these are also subject to temporal changes as the physico-chemistry of heaps evolves during leaching. Other selection pressures will apply in certain situations, e.g., for mineral-oxidising prokaryotes that are able to tolerate elevated concentrations of salt (NaCl) as well as extreme acidity and transition metals.

1.5 Commercial Bioleach and Biooxidation Operations in 2020

Biomining was described above as a niche technology, but the encouraging reality is that within the mining industry, bioleaching is considered a viable alternative hydrometallurgical process for extraction of base metals, and biooxidation competes with pressure oxidation or roasting for pre-oxidation of refractory gold-bearing ores and concentrates. A section of the *SME Mining Reference Handbook* has devoted a chapter to bioleaching since 2002 (Briggs 2002) and major metallurgical conferences (CIM) interleave biohydrometallurgical papers among other hydrometallurgical presentations. The comprehensive *SME Mineral Processing and Extractive Metallurgy Handbook* published in 2019 (Dunne et al. 2019) dedicated two chapters to bioleaching and agitated bioleach reactors within the section devoted to hydrometallurgy. Therefore, there can be no question that bioleaching and biooxidation are accepted unit processes in mineral processing, though they have a limited range of applications compared to more common unit processes such as conventional heap leaching with sulfuric acid (for copper) and high-temperature oxidation (for gold). Ultimately the mineralogy and deportment of the base or precious metal, and the economics relative to the location and grade of the deposit, will drive the decision of which process(es) to build a mine around.

More than a decade since the last edition of *Biomining*, there have been several notable long-term studies of commercial copper bioleach operations around the world. In Chile, a focused effort to develop a logic-based control system for heap bioleaching at the Escondida mine incorporated microbiological, genetic, and production information with machine learning to optimise the bioleach component of the overall operation (Demergasso et al. 2018). Heap aeration, specialised material handling, and inoculation were key components of the Bio-Leach Sulfide Project. The Escondida mine, a joint venture of BHP Billiton, Rio Tinto, and JECO Corporation is the world's largest copper mine, produced nearly 1.2 million tonnes of copper in 2020, or about 6% of the world's copper and over 20% of Chile's national production (2020 preliminary data). For nearly 15 years, Biosigma, a joint venture between Codelco and JX Nippon Mining and Metals operated in Chile to develop microbiological improvements in copper heap leaching, including dozens of Chilean and US patents. JX Nippon Mining and Metals sold its stake to Codelco in 2015, after which Biosigma became a part of Codelco Tech SpA, and was disbanded in 2017. At Codelco's Radomiro Tomic mine, Biosigma implemented a novel fluidised bed bioreactor to cultivate microorganisms for heap inoculation that was tested at kiloton scale. At the Zijinshan mine in China, a body of work has described the directed manipulation of environmental conditions to influence microbial populations and activities in order to improve heap leach performance that benefits both copper and gold production. This practice is being transferred to other mines operated by Zijin Mining Company including the Monywa mine in Myanmar (Chen et al. 2020). These refinements and advances are further described in Chaps. 8–10.

In refractory gold ore biooxidation, BioMin (formerly GoldFields) was acquired by mining industry support giant Outotec (now Metso Outotec) in 2016, and the BIOX® process is now another product offering in that company's suite of hydrometallurgical process options that include the related ASTER™ thiocyanate biodegradation process and MesoTHERM® elevated temperature BIOX®. Coupled with Metso Outotec's strong capabilities in large-scale, stirred-tank reactor systems, it can be anticipated that the BIOX® process will continue to be refined and improved to increase its competitiveness with roasting and pressure oxidation for pre-oxidation of refractory gold ore concentrates. The BIOX® process is currently operating on 3 continents at 7 different mines and accounts for 1% (approximately 1.1 million oz. in 2020) of global gold production and will be further described in Chaps. 4 and 11. According to Metso Outotec, several new projects are in the pipeline for North America.

1.6 Scope of the Current Textbook

This book is the successor to two previous texts on biomining that became firmly established as major references for this area of biotechnology: *Biomining: theory, microbes and industrial practices* (Rawlings 1997) and *Biomining* (Rawlings and Johnson 2007a). It provides both an update on the topic and projects on how the technology is developing and expanding into potential new areas, with contributions from experts and leading authorities from industry, government agencies, and academia from around the world. The book comprises six parts. The first (this chapter) describes the context and development of biomining, while Part II has three chapters that describe the engineering designs and operation of biomining systems (bioheaps and stirred tank systems) and an up-to-date account of the bioprocessing of refractory gold ores. Part III focuses on the microbiology of biomining, with individual chapters covering the biodiversity of acidophiles and how they mediate mineral dissolution, the cultivation and molecular techniques available to study them, and the microbial ecology of bioheaps, stirred tanks, and abandoned mine wastes. Part IV highlights commercial mineral bioprocessing operations carried out in different parts of the world (China, Chile, Peru, Russia, Kazakhstan, and Finland), while Part V describes four areas of biohydrometallurgy that are emerging as potential new areas: bioleaching in the presence of elevated salt concentrations, bioprocessing electronic wastes, reductive bioleaching of oxidised ores, and the use of microorganisms to recover metals from acidic waste and process waters. Finally, Part VI considers, in a concluding chapter, how biomining technologies may develop and be applied in the twenty-first century, in the context of ever-expanding demand for metals and the need for sustainability.

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