



# Mineral Processing in Bioreactors: Fundamentals and Design Aspects

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## Abstract

Bioreactors have proven capabilities to facilitate the bio-metallurgical extraction of important major and trace metal commodities, even from low-grade mineral ores and mine wastes. Yet, effective mineral processing with bioreactors requires a detailed and quantitative understanding of the underlying biogeochemical and mineralogical processes, the prevailing mass and energy transport limitations, as well as process control and monitoring concepts. In this chapter, we aim to introduce critical aspects of bioreactor design and operation, ranging from the pre-conditioning and properties of bioreactor material feeds, relevant geochemical reactions, kinetics, microorganisms and extraction conditions to process and performance control aspects. We also discuss select industrial applications, case studies and emerging technologies. We conclude that mineral processing with bioreactors is a challenging task that requires the input of concepts from various scientific and engineering fields and will play a critical role in satisfying the growing demand for metals and sustainable resource extraction in future.

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## 1 Introduction

Our current quality of life is highly dependent on the various functional properties of major and trace metals, whether used as fundamental building materials or for high-tech applications in space travel, nanomedicine or the clean energy transition (Akcil et al., 2020). To meet growing global demand, the prospecting, exploration, mining and processing of metal ore has been—and continues to be—expanding (Lee et al., 2020; Northey et al., 2017). However, declining ore grades near the Earth's surface bring challenges to the continued metal supply. In addition, increasing ore complexities and growing societal and environmental consciousness require more advanced extraction technologies and energy-efficient, environmentally sustainable production (Lottermoser, 2007). Therefore, the last decades have seen major innovations in science and engineering fields across the mining cycle, and novel approaches to metal recovery are no exception (Aznar-Sánchez et al., 2019; Litvinenko & Sergeev, 2019; Lusty & Gunn, 2014).

Conventional metal recovery techniques are primarily classified as pyrometallurgical, hydrometallurgical and electrometallurgical. Pyrometallurgical processes include ore calcining, roasting and smelting to convert target metals to their elemental form at elevated temperatures (Habashi, 2009). Hydrometallurgical techniques extract metals through solid–liquid interaction (i.e., leaching), which can be cost-effective for metal recovery from specific mineral hosts (Bautista, 2013; Peters, 1992). In electrometallurgy, metals are mobilised, deposited or plated in an electrolytic cell that may contain an aqueous or non-aqueous solution (Popov et al., 2007). Each of these techniques has intrinsic merits and demerits, and in industrial operations, one may encounter a combination of them. The focus of this chapter is on aspects of (bio)hydrometallurgy; reviews on other recovery techniques can be found elsewhere (e.g., Habashi, 1993; Mambote et al., 2000; Mooiman et al., 2005).

Hydrometallurgical approaches require relatively low capital investment and operational costs (Schlesinger et al., 2011; Stanković et al., 2020) and they are increasingly feasible for low-grade ore deposits or even below-grade materials otherwise considered waste (e.g., heap or dump leaching; Ilankoon et al., 2018). However, increasing ore complexities challenge successful hydrometallurgy and many oxidised ores have been extensively mined and exhausted, leaving more reduced and gangue-loaded (i.e., refractory) ores for future mining (Kaksonen et al., 2018; Northey et al., 2014; Prior et al., 2012). Adaptation to improve the efficacy of conventional hydrometallurgical routes is therefore required.

The use of microorganisms to promote metal recovery in hydrometallurgy has long been considered in metal processing (Ehrlich, 2004), and there are now industrial-scale facilities dedicated to metal extraction using microorganisms. This field is known as biohydrometallurgy or biomining (herein referred to as biometallurgy), encompassing two main domains: bioleaching and biooxidation (Schippers et al., 2014). Bioleaching promotes the leaching of metals into an aqueous solution, whereas biooxidation enhances the removal of gangue rock matrix while leaving targeted ore minerals behind (Acevedo, 2000; Kundu & Kumar, 2014). Bioleaching is particularly popular in the copper (Cu) industry, where it is used for ~20% of global production (Yin et al., 2018). Bioleaching of chalcopyrite ( $\text{CuFeS}_2$ ), the most abundant Cu resource at present (Vardanyan & Vardanyan, 2021), may even outcompete the recovery efficiencies obtained in conventional hydrometallurgical processing (Vakylabad et al., 2022). Biooxidation, in turn, is heavily deployed in the gold (Au) industry, specifically for refractory ore deposits that are not favourable for cyanidation but where gangue removal may be facilitated by bacterial oxidation (Khaing et al., 2019; Sugai & Sasaki, 2019). Although extraction using biometallurgy currently constitutes only ~5% of annual global Au processing, a shift towards bioextraction is noticeable (Kaksonen et al., 2020a, 2020b). Successful biometallurgical operations are also reported for various other base and precious metals, e.g., Zn, Ni, Mn, Co, Mo and U (Ghassa et al., 2014; Sugai & Sasaki, 2019; Watling, 2015; Watling et al., 2015), emerging technology critical elements (e.g., Swain, 2017) as well as Rare Earth Elements (REE) (Rasoulnia et al., 2021).

Industrial applications of biometallurgy are plentiful and can be performed in heaps, dumps, in situ, as well as in bioreactors. Conventionally, heap and dump leaching are performed for low-grade ore deposits (e.g., Cu grade < 1% (Saldaña et al., 2021)) with nutrient-rich solutions allowed

to percolate large pads of material. Because the geochemical reactions that mobilise metals from low-grade ore deposits can be slow under the ambient conditions that prevail in heaps and dumps, the economic recovery of a target metal may take years (e.g., Gericke, 2012; Kaksonen et al., 2018; Wu et al., 2007). In situ leaching follows a similar strategy, where nutrient and/or microorganism-enriched solutions are introduced to an intact ore deposit underground. This technique has been particularly successful in uranium mining (Yin et al., 2018). However, overall, metal recovery rates obtained in heap, dump and in situ leaching operations may be limited by a reduced packing permeability and complex pore networks that cause long retention times, low  $\text{O}_2/\text{CO}_2$  transfer rates and mineralogical heterogeneity (Fernando et al., 2020a, 2020b; Petersen, 2016; Vriens et al., 2019, 2020a). In addition, microorganism proliferation and activity depend on prevailing temperatures, redox potential, physicochemical material heterogeneity (Rawlings, 2005) and infiltration rates of the solution. Poor control or suboptimal conditions of these parameters hinder uniform bacterial colonisation and reduce metal recovery (Fagan et al., 2014). Also, because of the relatively large spatial footprints and prolonged operations required for economic metal recovery, heap and in situ leaching require careful and long-term management and environmental monitoring to prevent deleterious effects on the ground and surface waters (Fernando et al., 2018; Lottermoser, 2007).

In this regard, performing similar biogeochemical metallurgical reactions under fully enclosed bioreactor conditions often increases control and operational flexibility and monitoring capabilities, ultimately improving efficiency. For example, reaction kinetics can be expedited for enhanced recovery rates, i.e., days compared to years in heap leaching operations. Bioreactors may also be more readily adapted to changes in feed properties, offer processes to be automated at various scales and generally allow for better management of waste streams.

In this chapter, the following aspects of bioreactor design are discussed:

- i. processes and parameters in bioreactors used for mineral processing,
- ii. process control and (novel) monitoring techniques (e.g., Artificial Intelligence),
- iii. selected industrial applications, and
- iv. opportunities and emerging directions.

A selection of previous works on various aspects of bioreactor design and operation for biometallurgy is presented in Table 1.

**Table 1** Overview of selected reviews relevant to bioreactor design and operation, covering a range of reactor types and methods

Article/chapter title	References
The use of reactors in biomining processes	Acevedo (2000)
Bioleaching: A microbial process of metal recovery; A review	Mishra et al. (2005)
Bioreactor design fundamentals and their application to gold mining	Acevedo and Gentina (2007)
Biomining	Rawlings and Johnson (2007)
How will biomining be applied in future?	Brierley (2008)
Biodiversity and interactions of acidophiles: understanding and optimising microbial processing of ores and concentrates	Johnson (2008)
Biohydrometallurgical prospects	Brierley (2010)
Progress in bioleaching: Fundamentals and mechanisms of bacterial metal sulphide oxidation	Vera et al. (2013)
The role of microorganisms in gold processing and recovery—A review	Kaksonen et al. (2014)
Review of biohydrometallurgical metals extraction from polymetallic mineral resources	Watling (2015)
Microbiological advances in biohydrometallurgy	Watling (2016)
A review of sulphide minerals microbially assisted leaching in stirred tank reactors	Mahmoud et al. (2017)
The evolution, current status and future prospects of using biotechnologies in the mineral extraction and metal recovery sectors	Johnson (2018)
Recent progress in biohydrometallurgy and microbial characterisation	Kaksonen et al. (2018)
Biotechnology for environmentally benign gold production	Natarajan (2019)
Prospective directions for biohydrometallurgy	Kaksonen et al., (2020a, 2020b)

## 2 Processes and Parameters in Mineral Processing Bioreactors

### 2.1 Metallurgical Unit Operations

Bioreactor design for hydrometallurgy and mineral processing requires consideration of the entire mineral processing system. Different unit operations may be involved before and after bioreactor operation (Fuerstenau & Han, 2009), although bioreactors in mineral processing generally occur in the final stages of the overall extractive process. This means that preceding unit operations are critical to the success of a biometallurgical reactor: ore or ore concentrate particles need to be carefully characterised and their properties translated into engineering design parameters. For instance, pre-conditioning through size reduction and separation based on mineralogy is required to obtain optimal mass transfer through precise control of, e.g., temperature, aeration and mixing (Brierley, 2008).

#### a. Particle characterisation

Geometallurgical variables at the processing plant largely dictate the engineering parameters required for designing bioreactors. Such variables can be classified into (1)

primary variables that refer to the rock attributes (e.g., mineralogy, lithology, grain size, metal grade, texture, deleterious elements, among others) and (2) response variables, which are properties derived from the material's response to the process (e.g., grindability, flotability, acid-soluble metal content, acid consumption, metallurgical recovery, intact rock strength) (Coward et al., 2009). Primary variables can be retrieved from core logging and mineralogical, geochemical and physical assays. Primary variables integrated with information derived from the deposit block model allow one to constrain these properties spatially, enabling the development of processing plants and bioreactors that can account for temporal variability (Coward et al., 2009; Dominy et al., 2018). Response variables are derived from geometallurgical test work conducted at laboratory and pilot-scale facilities. The integration of data retrieved from primary and response variables enables an improved prediction of the metallurgical performance of the bioreactor (e.g., metallurgical efficiency, product quality, energy, and reagent consumption during processing) and supports the definition of operational parameters (Dominy et al., 2018; Lund & Lamberg, 2014; Pell et al., 2021). In addition, the mineral characterisation unit can also incorporate environmental variables (e.g., carbon footprint, particle emissions)

to proactively design processes with better environmental performance (Pell et al., 2021).

#### b. Size reduction and liberation

Size reduction is achieved by comminution, which is the process of blasting, crushing and grinding material to the required particle size. Comminution aims to liberate valuable minerals from gangue to the coarsest permissible particle size. The material's breakage increases the reactive surface area to facilitate the geochemical reactions of microorganisms in a bioreactor (Fuerstenau & Han, 2009). A critical aspect of size reduction is the energy required for comminution, which depends on the hardness of the rock, the feed size and the targeted size for liberation (Gupta & Yan, 2016). Size reduction is an energy-intensive process that accounts for ~50% of the operating costs of a mineral processing plant, with grinding accounting for 50% of the energy consumption of the unit (Radziszewski, 2013). As a result, a significant challenge lies in achieving a particle size that is large enough to ensure energy savings but small enough to allow sufficient interaction between microorganisms and the ore or gangue minerals (Herbst et al., 2003). The optimum particle size is determined partly by the grain size and mineral texture (i.e., relationships of the minerals at the grain scale). In particular, bioreactors and flotation circuits require exposure of at least a fraction of the mineral's surface. Generally, target sizes for metal sulphides range between 100  $\mu\text{m}$  for coarse-grain ores and 10  $\mu\text{m}$  for fine-grain ores (Evans et al., 2015; Wills & Finch, 2016).

#### c. Concentration

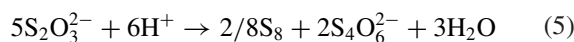
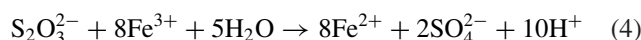
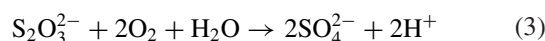
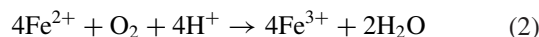
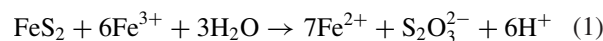
Before introducing feeds to a bioreactor, further separation of metals from gangue particles may be required. The concentration methods depend on material properties such as density, magnetic susceptibility and electric conductivity (Fuerstenau & Han, 2009; Wills & Finch, 2016). Common techniques include (optical) sensor-based sorting, gravity concentration, froth flotation, and electrostatic and magnetic separation, all of which may be deployed in combination with a bioreactor unit. Biometallurgy can be used as a pre-treatment step to enhance the flotation performance or after flotation to complete the extraction of the metals.

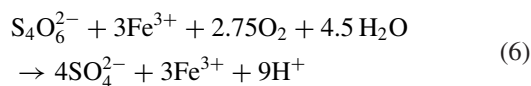
## 2.2 Biometallurgical Mechanisms

Achieving successful metal extraction in bioreactors requires optimum leaching conditions that allow controlled microbial activity and growth (Sajjad et al., 2019). Such optimal conditions will vary widely depending on the type of ore, particle size and the involved microbial consortia, which may require different temperatures and pH, nutrient levels and oxygen and  $\text{CO}_2$  content (Acevedo & Gentina,

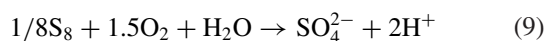
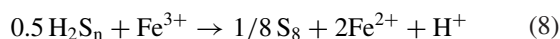
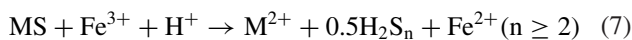
1989; Sajjad et al., 2019). Regardless of the targeted process, establishing and maintaining optimal bioleaching conditions requires one to quantitatively understand variability in material feeds (Sect. 2.1), the major biogeochemical reactions (including stoichiometry, thermodynamics, kinetics and the biocatalytic effects of microorganisms), the compatibility between microorganisms and the ore-bearing mineral slurry, and the controls of the prevailing conditions on microbial growth and activity, among others. Bioleaching in engineered systems may be performed by diverse microorganisms, including bacteria, archaea and fungi. There have been many advances in metallurgical microbiology over the past decades, and the reader is referred to existing reviews on the diverse microbiology of bioleaching systems (Bosecker, 1997; Kundu & Kumar, 2014; Schippers et al., 2010; Watling, 2016).

Metal recovery from sulphide minerals is typically achieved through the activity of chemolithotrophic bacteria, well-known species of which include *Acidithiobacillus ferrooxidans* and *thiooxidans*, *Leptospirillum ferriphilum*, as well as thermophile archaea such as *Sulfolobus metallicus* or *Acidianus* sp. (Blackmore et al., 2018; Edwards et al., 2000; Jia et al., 2019; Sajjad et al., 2019; Schippers et al., 2010; Schrenk et al., 1998). Genetic engineering of these and other microorganisms to improve biometallurgical extraction is an active field of research (Kaksonen et al., 2020a, 2020b). The mechanisms by which microbial species convert poorly soluble sulphides into metal-sulphates may vary. Two types of pathways are typically distinguished based on the acid-solubility of the targeted sulphide: the thiosulfate pathway for acid-insoluble sulphides (e.g., pyrite [ $\text{FeS}_2$ ]) and the polysulfide pathway for acid-soluble sulphides (e.g., sphalerite [ $\text{ZnS}$ ] or galena [ $\text{PbS}$ ]). Acid-insoluble pyrite oxidation by  $\text{Fe}^{3+}$  generates acids, dissolved thiosulfate ( $\text{S}_2\text{O}_3^{2-}$ ) and  $\text{Fe}^{2+}$  that can be re-oxidised to  $\text{Fe}^{3+}$  Eqs. (1 and 2), after which dissolved  $\text{S}_2\text{O}_3^{2-}$  may be further oxidised to sulphate ( $\text{SO}_4^{2-}$ ), either directly (Eq. 3, 4) or via (poly)thionate intermediary species (Eq. 5–6), according to the following reactions (Schippers, 2004):





The oxidation of acid-soluble sulphides also occurs through  $\text{Fe}^{3+}$  and proton attack, but instead releases divalent metal cations and sulphide radicals (Eq. 7), the latter which are further oxidised via elemental S to  $\text{SO}_4^{2-}$  (Eq. 8, 9) (Vera et al., 2013):



The catalysis of the above reactions by autotrophic bacteria increases reaction kinetics by orders of magnitude (Nordstrom, 1982), whereby the oxidation of  $\text{Fe}^{2+}$  to  $\text{Fe}^{3+}$  by oxygen is considered rate-limiting (Singer & Stumm, 1970), particularly under higher pH values where Fe-oxides are poorly soluble. Overall, microbially mediated oxidation of sulphides to sulphate involves the transfer of 7 or 8 electrons for each S atom, depending on whether the mineral is a mono-sulphide or di-sulphide. Thus, it constitutes a complex, multi-step process that involves biochemical and electrochemical reactions in which the kinetics of each step are affected by factors such as pH,  $\text{pO}_2$ , and the specific surface area and morphology of the sulphide (Blowes et al., 2014; Evangelou, 1998; Evangelou & Zhang, 1995; Keith et al., 2018). Different microbial species may be active at different steps in both pathways (e.g., performing Fe- versus S-oxidation), but species such as *Acidithiobacillus* and *Leptospirillum* are involved in steps in both pathways (Johnson, 2018; Schippers & Sand, 1999). These bacteria are acidophilic and have optimal growth conditions around pH 2–3 but can survive up to pH 6–7 (Nordstrom, 1982). Neutrophilic S-oxidising bacteria may coexist with acidophilic bacteria and contribute to oxidative sulphide dissolution under neutral conditions (Skłodowska & Matlakowska, 2007). In addition to the above mechanisms where bacteria oxidise dissolved Fe that can then attack metal sulphides, certain microbial species can oxidise mineral surfaces directly or produce dissolved organic acids that act as chelating agents that promote dissolution. Depending on the mechanism involved, microorganism activity is thus desired closer to or further from the mineral interface (Fig. 1). For instance, thiobacilli may secrete extracellular polymeric substances (EPS) that may enhance leaching and facilitate attachment of the bacteria to the mineral surface, affecting solute-surface exchange. Detailed information on mineralogy-dependent S-oxidation pathways, including the kinetics of microbial catalysis, is available in Vera et al., 2013;

Rohwerder et al., 2007; Schippers et al., 2010; and Tu et al., 2017, among others (Table 1).

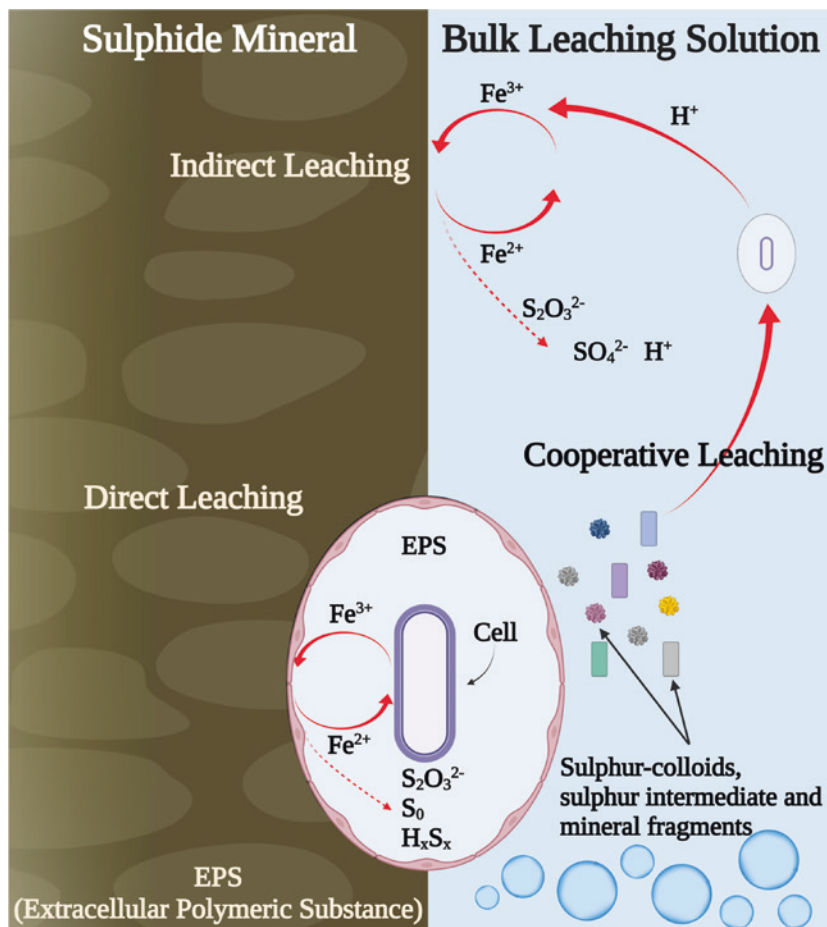
In addition to oxidative bioprocessing, hydrometallurgical processes using microorganisms can also be reductive, e.g., the dissolution of oxide minerals in anaerobic environments. Examples include a variety of commodities (e.g., Co, rare earth elements) that can be mobilised from materials such as laterites under reducing conditions (Johnson et al., 2013; Nancuqueo et al., 2019; Smith et al., 2017; Yang et al., 2019).

### 2.3 Metallurgical Bioreactor Design

Bioreactors for mineral processing have various designs: batch reactors, stirred tanks, column reactors, including fixed or fluidised beds, membrane, bubbling or air-lift columns, as well as solid substrate- and heap reactors (Gonzalez-Sanchez et al., 2008; Midha et al., 2012; Sahinkaya et al., 2011). From a chemical engineering perspective, bioleaching in agitated aerated tanks is typically considered a continuous-flow and steady-state process (Acevedo & Gentina, 2007). Regardless of the reactor mode and configuration (e.g., in serial versus parallel arrangement), the design and optimisation of a hydrometallurgical bioreactor process require (i) a time-dependent characterisation of material feeds, which might not be of constant quantity and quality in mining operations (Sect. 2.1), (ii) a quantitative understanding of the occurring reactions including stoichiometry, thermodynamics, and (bio)kinetics (Sect. 2.2) and (iii) balance models for mass and heat at a variety of spatiotemporal scales. Ultimately, the interplay between reaction- and transport processes poses a critical control on product formation and selectivity, efficiency (e.g., mass transfer versus kinetic rate limitations, power consumption), yield, reactor stability, etc. (Acevedo & Gentina, 2007; Morin, 2007). While not intended to review reactor engineering principles, this section addresses some key bioreactor design aspects.

Firstly, a kinetics study will reveal reaction rates, including substrate consumption and product synthesis rates, controlling kinetic factors, reaction orders and by-product formation. Well-characterised reactor kinetics may help avoid mineral passivation with biofilm or precipitation of secondary mineral phases (e.g., jarosite) that can reduce mass transfer (Kaksonen et al., 2014; Kartal et al., 2020), and identify potentially toxic constituents that can inhibit microorganism growth (e.g., chlorides, cyanides; Natarajan, 2019). A quantitative understanding of intermediary product formation and their thermodynamic versus kinetic stability in a bioreactor is critical. Still, when potentially hundreds of reactions are involved, and intermediary species are not rate-limiting on the scales of operation, the overall stoichiometry may be considered. The kinetics of

**Fig. 1** Schematic illustration of various bio-assisted leaching and oxidation mechanisms in the presence of sulphide minerals (modified after Mahmoud et al. (2017) and Rawlings (2002))



oxidative dissolution of sulphide minerals  $r$  [units of mass or moles per volume or surface per time] may be generically expressed as

$$r = k[A]^\alpha[B]^\beta \dots \quad (10)$$

where  $k$  is the reaction rate constant and  $[A]$  and  $[B]$  are the aqueous activities of solutes involved in the reaction kinetics. In the case of metal sulphide oxidation, these may include  $[\text{Fe}^{3+}]$ ,  $[\text{O}_2]$ , or pH ( $[\text{H}^+]$ ). The exponents,  $\alpha$ ,  $\beta$ , etc., are the reaction orders concerning components A, B, etc. Typically, reaction orders depend highly on the targeted mineral assemblage and leaching conditions tested. For instance, pyrite oxidation may depend on the aqueous proton activity to an order of  $-0.5$  to  $-0.11$  and the dissolved  $\text{Fe}^{3+}$  activity to an order of  $0.3$  to  $0.58$  (Holmes & Crundwell, 2000; Humnicki & Rimstidt, 2009; Williamson & Rimstidt, 1994). Certain design parameters such as temperature may be readily accounted for by adjusting  $k$ , e.g., using Arrhenius-type relationships. However, across widely variable conditions, the entire microbial community and bioreaction pathway (and thus kinetics) may change depending on the targeted process. Parameters such as liberated surface area and

mineral morphology will affect bulk reaction rates and may be explicitly expressed in a rate equation as well. However, due to challenging quantification, microscale parameters often remain unresolved in the reaction rate constant  $k$ , complicating the extrapolation of kinetic studies across different applications (Vriens et al., 2020b). Overall, large variability may occur between bioreactor conditions, and kinetic reaction descriptions often have non-negligible uncertainties (Crundwell, 2000). To facilitate pragmatic reactor design, certain kinetic parameters can be reasonably assumed constant (e.g., temperature or bulk slurry pH may be adequately controlled). The resulting rate equations subsequently relate process kinetics directly to design parameters, such as total substrate or biomass  $M$ , average substrate particle size  $d_{50}$ , temperature  $T$ , or pH:

$$r = f(M, d_{50}, T, \dots) \quad (11)$$

In addition to relevant reaction kinetics, a series of mass and energy balance equations form the foundation of bioreactor design. These will help define reactor and flow dimensions, ensure residence and mixing times allow for reactions to proceed as desired, avoid needless washout,

and that the relevant mass and heat transfer processes ensure the reactor system is controlled and stable (Belyi et al., 2018; Miller, 1997). These balance equations look different depending on the bioreactor type and processes involved. Mass-balance (change in mass in the system with volume  $V$  over time  $[d(Vc)/dt]$ ) can be generalised in the form:

$$\frac{\partial(Vc)}{\partial t} = \sum_{i=1}^n F_i(c_{0,i} - c_i) \pm rV \quad (12)$$

where  $c$  is reactor concentration,  $c_0$  feed concentration,  $F$  is a mass flow rate (if present) and  $r$  a kinetic rate expression (Eq. 11; Fig. 2). There may be various flows  $F$  carrying different  $c_0$  into and  $c$  out of a reactor system, as well as different rate expressions (zeroth, first, second, fractional orders) for the involved reactions: typically, a number of inter-dependent mass-balance statements with appropriate boundary conditions is required for different solutes of interest. For bioleaching operations targeting sulfidic ores, these include balances for the targeted metal(s) of interest as well as other abundant metals (e.g., Au, Cu, Ni), S and potential intermediary species, other elements of concern,

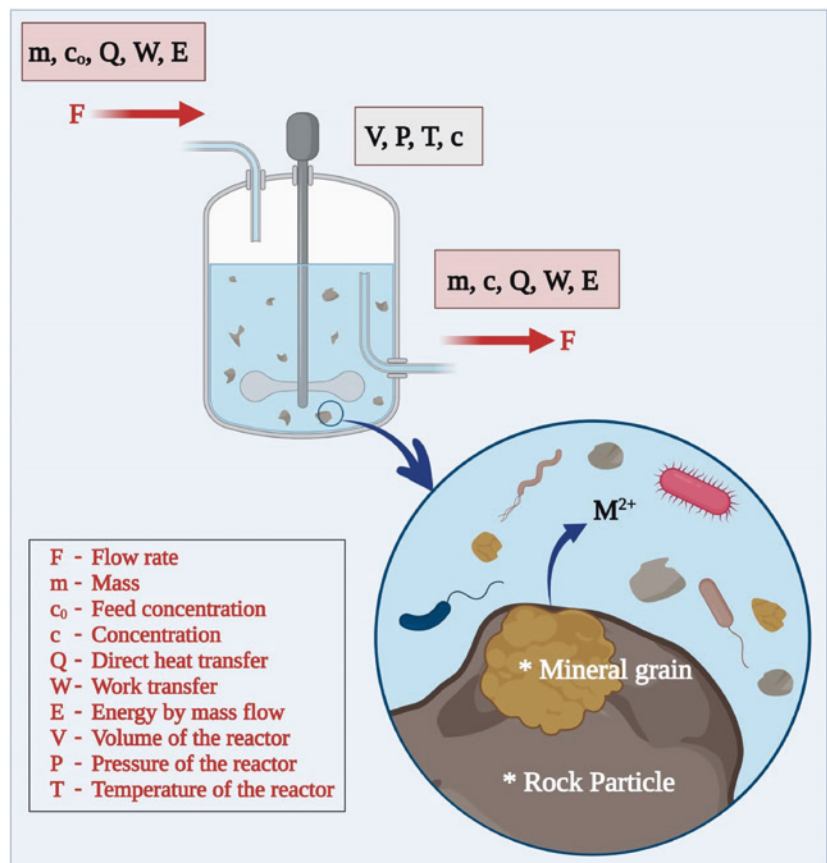
as well as nutrients (N, P) and gaseous species such as oxygen and  $\text{CO}_2$  (i.e., carbon and oxygen uptake rates).

Most biometallurgical processes are reactor-operated under mesophilic or moderately thermophilic conditions (20–50 °C; Rawlings et al., 2003). Moderate thermophiles in bioleaching processes may have kinetic advantages over mesophilic conditions, can grow at higher pulp densities than thermophiles (Nemati et al., 2000) and tolerate higher catalyst concentrations such as Ag (Gómez et al., 1999). Because microorganisms have optimum temperatures for their metabolic activity (Norris et al., 2000), temperature is a critical parameter to control bioleaching and biooxidation processes and guarantees high conversion rates. Energy balance equations account for total energy dynamics in a bioreactor system over time ( $dE/dt$ ) and can be generalised as

$$\frac{\partial E}{\partial t} = (Q_{in} - Q_{out}) + (W_{in} - W_{out}) + (E_{in} - E_{out}) \quad (13)$$

in which  $Q$  is direct heat transfer to and from the reactor,  $W$  is work transfer, and  $E$  is the energy introduced or removed by mass flow. Energy  $E$  is the sum of internal ( $mU_i$ ), kinetic ( $mv_i^2/2$ ) and potential energy ( $mgz_i$ ). For open system balances, the kinetic and potential energy components are

**Fig. 2** Schematic illustration of the various mass and energy flows in an aerated stirred tank bioreactor



distinguished from internal energy and flow work and considered as enthalpy  $H$ , which allows for facile incorporation of the energies produced or consumed by chemical reactions in the energy balance. Bioreactor design may involve consideration of heat generation or removal by metabolism, agitation, aeration, phase change (e.g., evaporation) and exchange with surroundings (Van't Riet & Tramper, 1991).

Typical operation under steady-state conditions and prioritisation of select major mass and energy transfer processes allow for reactor design with simplified balance statements. However, many simultaneous multiphase transport processes occur in a bioleaching operation: efficient heat transfer is needed to operate the bioreactor at the desired optimal microbial growth temperature, nutrients must reach surface-bound and suspended cells, metabolic products must migrate from the cells to the liquid, and solubilised species must be transported from the mineral surfaces to the bulk liquid. Thus, identification and parameterisation of the relevant mass- and heat transfer processes and the corresponding material properties (e.g., convective heat transfer coefficient of a slurry or effective diffusivity of a solute) is required to optimise bioreactor performance.

Another important consideration in bioreactor design is the autocatalytic nature of microbial growth. In a bio-process, biomass concentration must remain high enough to achieve a high yield, but not too high when organisms proliferate on the reactor walls or stirrer or cause fouling and clogging. An additional material balance for cell density is often required, deploying, e.g., a Monod-type equation for microbial growth kinetics:

$$\mu = \mu_{\max} \frac{[S]}{K_S + [S]} \quad (14)$$

where  $\mu$  is a specific growth rate,  $\mu_{\max}$  is a maximum growth rate,  $[S]$  is the limiting substrate concentration, and  $K_S$  is the Monod constant. Bioreactor design should also consider surface attachment: recalcitrant and poorly soluble sulphides can have low affinity and substantial cell growth, but low substrate-microorganism affinity (corrected Monod's saturation constant) may require the use of material treatment or additives (Crundwell, 2000; Morin, 2007).

The physical environment affects biological performance in other ways also. Bioreactors are usually stirred to homogenise reactor content, maintain microbes and solids in suspension, and increase the rate of oxygen,  $\text{CO}_2$  and heat transfer. Under conditions of insufficient agitation, mass transfer processes may become reaction limiting, and the overall performance will decline because segments of bioreactor fluid have insufficient nutrients or inadequate pH or temperature (Bailey & Hansford, 1993). However, excessive stirring results in unnecessary loss of mechanical energy and high shear rates that may induce harm to shear-sensitive organisms and disrupt cell walls (Chong et al.,

2002). Overall, mechanical stresses, mass transfer and mixing, pH and temperature are all interrelated to biological growth and activity and affect bioreactor performance.

In summary, key design aspects for metallurgical bioreactors include.

- **Types of ore and particle size:** Bioreactors used to beneficiate polymetallic ores (e.g., Cu, Au, Ni) usually host varied associations of sulphide minerals which can be differently susceptible to bioleaching (Norris & Owen, 1993). Furthermore, the inherent variations within a deposit introduce mineralogical heterogeneity (Dominy et al., 2018). Therefore, the entire mineral assemblage requires careful study. Similarly, physical parameters such as particle size are dependent on the operation mode of the bioreactor. Finer particle sizes can facilitate microbial growth and accelerate reaction kinetics. However, they require increasing energy for milling and increased pulp density (typically 20–30% (Kundu & Kumar, 2014; Mahmoud et al., 2017)), which can negatively affect microbial growth, suspension, homogeneity and downstream settling processes (Acevedo & Gentina, 2007).
- **Microorganisms:** Bioreactors for bioleaching and biooxidation operations often have concurring species of bacteria, archaea or fungi in the same ecosystem and these different species may have variable optimal conditions for growth (Johnson, 2008) and capabilities to adapt to suboptimal conditions (Gomez et al., 1999). The reaction kinetics in bioreactors are strongly controlled by microbial diversity, density, spatial distribution and activity, which in turn are heavily affected by the mineralogical heterogeneity of the ore as well as many other physicochemical factors (temperature, redox potential, particle diameter, solid concentrations, see below). Overall, the bioleaching process efficiency depends on a delicate balance between the bacterial population and controlled growth conditions.
- **Temperature:** The optimal temperature window for bacterial growth depends on the type of microorganisms, often classified as mesophiles (20–40 °C), moderate thermophiles (around 50 °C) and extreme thermophiles (>65 °C) (Rawlings et al., 2003). A challenge for metallurgical bioreactors is that oxidative sulphide dissolution is highly exothermic (up to –1500 kJ/mol) and thus requires adequate control of the system's energy balance. Additional understanding of relevant thermo-hydrochemical feedbacks is important: e.g., the increasing temperature may be advantageous for improved reaction kinetics but could challenge gas–liquid mass transfer (e.g.,  $\text{O}_2$  solubility) (Sajjad et al., 2019).



- **pH:** The pH of the bioreactor medium influences the metabolism of microorganisms and geochemistry of the reactor system: different microorganisms have different optimal pH for growth, and the solubility of metals-of-interest and potential secondary mineral products is highly pH-dependent. Most bioleaching reactors exhibit strongly acidic conditions, where transition metals are typically very soluble.
- **Nutrients:** In bioreactions, nutrients may originate from the feed material, but sulfidic metal-ore materials typically contain little carbon, N and P, and supplements are commonly utilised. Reaction rates indirectly depend on a sufficient and effective supply of macro- and micro-nutrients.
- **Oxygen and CO<sub>2</sub>:** As most of the metal bacterial-assisted leaching processes are aerobic and chemolithotrophic, an adequate supply of oxygen and CO<sub>2</sub> is necessary. An adequate supply of these gases may be achieved by aeration and stirring reactor content, but oxygen and CO<sub>2</sub> need to be transported from air bubbles to the oxidation sites. Considering the low solubility of oxygen in aqueous solutions, gas mass transfer at the gas–liquid interface is a principal control of bioreactor efficiency (Garcia-Ochoa & Gomez, 2009; van Aswegen et al., 2007). Oxygen and CO<sub>2</sub> supply also present operating challenges for sequential bioleaching reactor systems, with the necessity to balance pressure and consumption in multiple reactors and additional regulation of CO<sub>2</sub> level when acid production is partially offset by carbonate buffering (Acevedo & Gentina, 2007; Kaksonen et al., 2018).

### 3 Bioreactor Process Monitoring and Control

#### 3.1 Monitoring

As discussed in Sect. 2, various parameters affect the biometallurgical process and require careful monitoring and control. Online monitoring is the logging of measured data directly into a control loop via sensors, whereas offline monitoring is sampling and logging data outside a control loop and usually involves manual entry (Malaguti et al., 2015). Offline methods may produce expired information, which may induce system instability when incorporated into the control loop. Computer-integrated solutions now allow for increasingly rapid (near) real-time data collection and processing and improved sensor technologies enable monitoring of the most critical physical (e.g., temperature, pressure), chemical (e.g., DO, pH) and biochemical (e.g., biomass) parameters within bioreactors at increasing resolution.

Sensors used in bioreactors can be of different types, including optical, electronic, electrochemical, electromagnetic, ultrasonic or bio-based (Busse et al., 2017). A sensor system extracts the parameter or system state of interest and couples it to an actuator framework (e.g., valve, pump) to trigger actions based on the sensors' output signals, thereby regulating the overall process. Numerous intricate subroutines are executed for efficient, robust and high-fidelity operations. Figure 3 illustrates a traditional bioreactor configuration and several parameters that can be measured. Sensors can be

- **Direct:** directly interact with the bioreactor medium to quantify a magnitude (e.g., temperature)
- **Indirect:** system not directly probed (e.g., external jacket temperature). Calibrated indirect measurement may be utilised to minimise interference with the process and increase sensor lifespan.
- **Inferential:** calculates the value of a parameter by measuring other variables that may be easier to probe (e.g., the fluid flow rate through a pipe inferred from a differential pressure transmitter, when the pressure in the pipe is directly related to the flow rate with constant fluid density).

Employing sensors to measure every parameter in a bioreactor process is not always practical: various parameters are challenging to probe at sufficient resolution (e.g., bacterial abundance or enzyme activity), and sensors may be susceptible to time constraints (temporal sensor resolution), and there may also be sensor placement challenges, e.g., due to corrosion/pH concerns or elevated temperatures (Botero & Álvarez, 2011). Considering these restrictions in bioreactor processes, monitoring may be limited to only the most critical parameters. These parameters portray known extensions to other parameters through the bioreactor model.

When sufficient substrate is available, the growth of microorganisms in a bioreactor may be modelled by

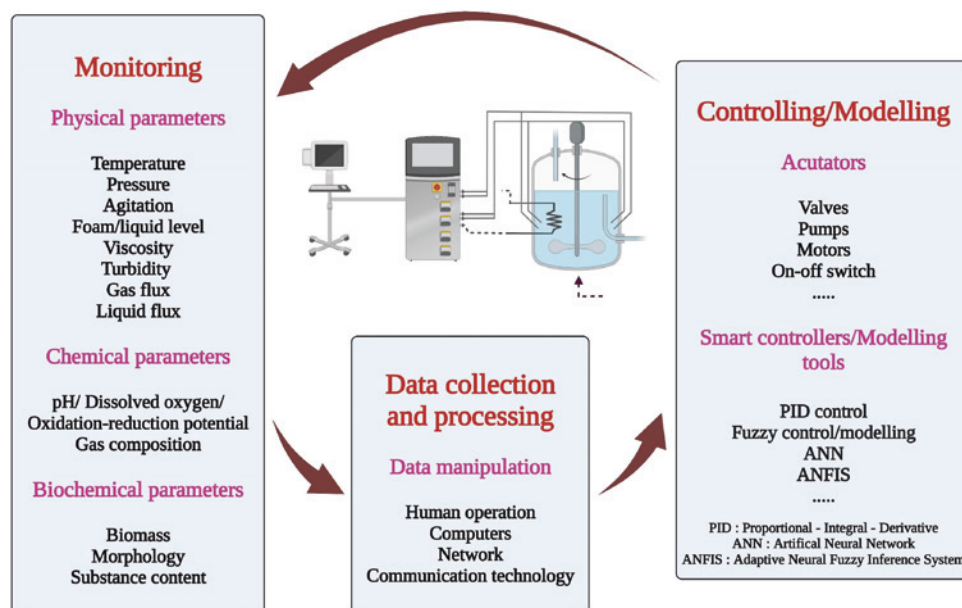
$$\frac{dX}{dt} = \mu(S)X \quad (15)$$

Here,  $X$  denotes the microorganism mass (or density), with a growth rate constant of  $\mu$ , which is contingent on the substrate  $S$ . In a continuous process, both inflow and outflow affect the growth mechanism and thus Eq. 15 may become

$$\frac{dX}{dt} = \mu(S)X + \frac{F_{in}}{V}X_{in} - \frac{F_{out}}{V}X_{out} \quad (16)$$

where the term  $\frac{F}{V}$  describes the dilution coefficient ( $D$ ), which can be used to describe biomass accretion from inflow and biomass loss through outflow under well-mixed conditions. Furthermore, Eq. 16 relies on a growth coefficient ( $\mu(S)$ ) that can be derived from Eq. 14. Thus, Eq. 16 may also be modified:

**Fig. 3** Monitoring, control and modelling aspects of a conventional bioreactor (modified after Wang et al. (2020))



$$\frac{dX}{dt} = \mu_{\max} \frac{[S]}{K_S + [S]} X + DX_{in} - DX_{out} \quad (17)$$

Bioreactor parameters discussed in Sect. 2 may be incorporated into Eq. 17 to assure an explicit description of microorganism growth. After defining the parameter space  $\Omega = f(\text{pH}, \text{temperature}, \text{DO}, \text{agitation speed}, \text{etc.})$ , the growth coefficient may be converted to

$$\mu(S, \Omega) = \mu_{\max} \frac{[S]}{K_S + [S]} f(\text{pH}) f(T) f(\text{DO}) \dots \quad (18)$$

and thereby the mass-balance equation for species X is converted to

$$\frac{dX}{dt} = \mu(S, \Omega) X + DX_{in} - DX_{out} \quad (19)$$

Equation 18 displays the nonlinearity of the microorganism growth process and intricate interdependence of the functional bioreactor parameters. A bioreactor process is highly dynamic and sensitive to subtle changes in parameter fluctuations, and modelling tools are often required to simulate and benchmark process control schemes (Malar & Thyagarajan, 2009). In addition, laboratory studies may disregard unresolved variances and treat dependencies as constants so that models are often poorly generalisable from system-to-system and highly specific instead. Increasingly, detailed monitoring of bioreactor dynamics can facilitate an understanding of reactor behaviour at high precision (subject to validation) but warrants the use of trained computer models to offset computational demands. Artificial Intelligence (AI) and Machine Learning (ML) techniques

are gaining precedence in reactor control due to the increased ease of rapid prediction with well-trained models (Babanezhad et al., 2020; Calzolari & Liu, 2021; Mowbray et al., 2021).

### 3.2 Bioreactor Control/Modelling Strategies

Control of bioprocesses generally requires at least several online measured parameters, including pH, temperature, DO and agitation (Portner et al., 2017). Other online monitoring techniques (e.g., in situ microscopy and impedance spectroscopy for cell concentration, or Infrared and Raman spectroscopy for metabolic compounds) are recent developments in online instrumentation (Abu-Absi et al., 2011; Pacheco et al., 2021). The fluctuation of these process parameters determines the control strategy, which needs to be optimised within the overall process. Observability is a measure of how well internal states can be elucidated by direct measurement (Dahleh et al., 2004): parameters such as temperature, pH, DO are examples of outputs directly probed in a bioreactor, but fully observable systems are scarce in practice (Maes et al., 2019). Most bioreactors are partially observable, and in control theory, a system requires full observability to permit full controllability (Nise, 2020). Controllability is defined as how well the system inputs can manipulate the system state. Observability and controllability are connected: if a system is partially observable, the controllability of the process is limited. Since many bioreactors are partially observable, they present an interesting control challenge for design engineers (Krishna et al., 2018; Wu et al., 2009). The following sections briefly discuss common control schemes for bioreactors.

### 3.2.1 PID-Based Control

Traditionally, fundamental bioreactor parameters such as pH, temperature or agitation are controlled by proportional-integral-derivative (PID) controllers (Chandra & Samuel, 2010). These controllers compare sensor inputs with a reference value (set value) and determine the error signal to control the system with static or adaptive schemes (Galvanauskas et al., 2019; Oladele & Shaibu, 2019). Regular PID controllers rely on constant tuning parameters (i.e., static), while others attempt to capture time-varying conditions (i.e., adaptive) through gain scheduling, tendency models and more (Akisue et al., 2021; Galvanauskas et al., 2019; Jayachitra & Vinodha, 2014). Further, details on PID control can be found elsewhere (e.g., Johnson & Moradi, 2005; Quiñónez et al., 2019). Although many bioreactor processes are nonlinear (e.g., Eq. 19), PID control is considered linear (Galvanauskas et al., 2019) yet may be applied within a limited (quasi-linear) region at nominal operating conditions of a bioreactor system.

### 3.2.2 Fuzzy Logic- and Artificial Neural Network-Based Control and Modelling

Fuzzy logic is a branch of Artificial Intelligence (AI) that informs the controller with expert knowledge of the underlying process using fuzzy variables, membership functions, a set of rules and a rule engine (Shaghaghi et al., 2013). Unlike Boolean outputs (i.e., TRUE or FALSE), fuzzy logic permits the controller to emulate human reasoning with scaled values, thereby incorporating control flexibility (Caramihai et al., 2013). Fuzzy logic models are sometimes combined with PIDs to capture nonlinear process features (Butkus et al., 2020). Artificial neural networks (ANNs) are considered universal AI approximators and are used extensively in nonlinear process modelling (Vyas et al., 2020). In contrast to fuzzy controls, ANN application eliminates the requirement of human intervention: ANNs self-learn based on correlations provided by a set of input and output data connected via optimised weights and transfer functions (Abdollahi et al., 2019). Adaptive Neuro-Fuzzy Inference Systems (ANFIS) are an example of combined Fuzzy Systems and ANN, where IF-THEN rules are specified using a feed-forward ANN, allowing the rule engine to self-learn, therefore harnessing the capabilities of both techniques (Xie et al., 2019). Other mixed control schemes include PID controllers with gain scheduling handled by a fuzzy inference system to effectively deal with process nonlinearities (Tamayo et al., 2019) and PID controllers coupled to ANNs that provide gain values (Tronci & Baratti, 2017).

Although fuzzy logic- and ANN-based controls are popular control schemes in many industries, examples of biometallurgical applications of these techniques remain relatively scarce in the published literature. Ahmadi and Hosseini (2015) used fuzzy models to predict Cu

bioleaching efficiencies, Bellenberg et al., (2018); Buetti-Dinh et al., (2019) explored ANNs for image analysis to resolve biofilm distribution and evolution (mineral surface attachment) in bioreactors, and Demergasso et al., (2018) and Soto et al., (2013) developed a decision support system for a heap bioleaching plant using historical data on ore mineralogy, solution chemistry and operational parameters. Additional information on potential applications of AI/ML for bioreactor control and modelling may be found in McCoy and Auret (2019), Rabbani et al., (2021) and Mishra (2021).

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## 4 Industrial Applications

The first industrial use of bioreactors for hydrometallurgy dates from 1958 at the Bingham mine, USA (Agioutantis, 2004; Yin et al., 2018). Subsequently, the development of bioreactor technology has been accompanying the steady growth of biometallurgy. The first-ever industrial-scale bioreactor installation was reported in 1986 with the BIOX™ process pioneered by Gencor (now known as Gold Fields), South Africa (van Aswegen et al., 2007). Originally designed for refractory Au ore oxidation, the BIOX™ process has also been explored to recover base metals (Batty & Rorke, 2006). Other noteworthy pilot plants include BHP Billiton's BioCOP™, BioNIC™ and BioZINC™ (Natarajan, 2018; Watling, 2008). Figure 4 presents an overview of metallurgical bioreactor technologies that have reached pilot- or industry-scale. This section discusses select examples of industrial applications of bioreactor-driven recovery of Au, Cu, Ni and Co.

### 4.1 Gold Industry

Industrial Au extraction often uses cyanidation, and removal of cyanide-consuming gangue is paramount to project economics. Biometallurgical techniques may be employed to biooxidise gangue minerals and remove them from the solid matrix.

The Fairview mine (South Africa) was among the first to commission the BIOX™ process (presently owned by Metso Outotec, Finland—Smart et al. (2017)) for the biooxidation of Au ore. The BIOX™ process has meanwhile found extensive utility as a pre-treatment technique in the Au processing industry, with 13 facilities deployed globally to date (Metso Outotec, 2021). The Fairview mine was designed for a 62 tonnes per day (tpd) feed and is still operational; the Kokpatas mine (Uzbekistan), capable of handling ~2,138 tpd of Au ore, is reported as the largest operating BIOX™ facility in the world (Brierley, 2008; Kaksonen et al., 2014; Natarajan, 2019).

**Fig. 4** 2021 overview of some bioreactor technologies deployed at industrial and pilot scale for precious and base metals.

\*: Currently under care and maintenance; \*\*: pilot plant; tpd: tons per day; kpd: kilograms per day. References: [1]: van Aswegen et al. (2007), [2]: Morin (2007), [3]: Mahmoud et al. (2017), [4]: Metso Outotec (2021), [5]: Brierley and Brierley (2001), [6]: Neale et al. (2000), [7]: Sovmen et al. (2009), [8]: Belyi et al. (2018), [9]: Batty and Rorke (2006), [10]: Dreisinger (2006), [11]: Brierley (2016a, 2016b), [12]: BRGM (2021), [13]: Palmer and Johnson (2005), [14]: Natarajan (2018), [15]: Natarajan (2019)

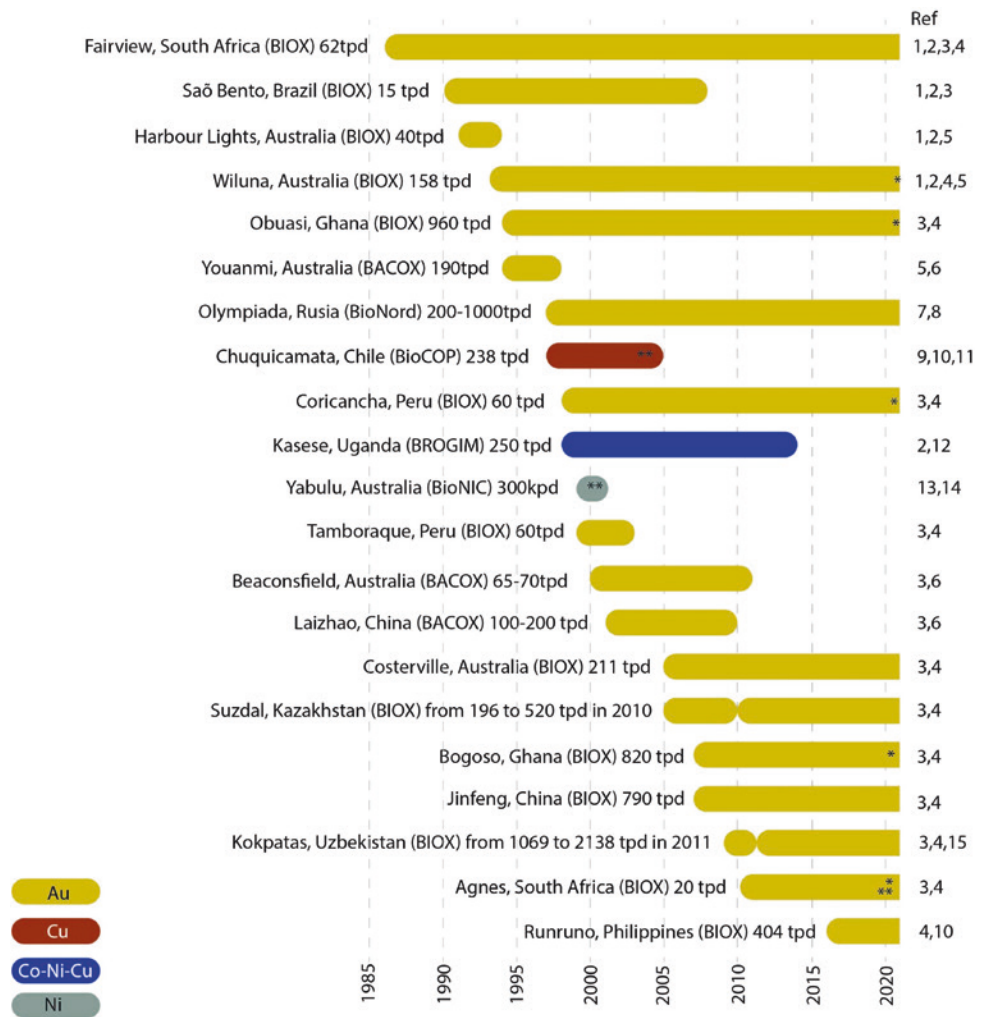
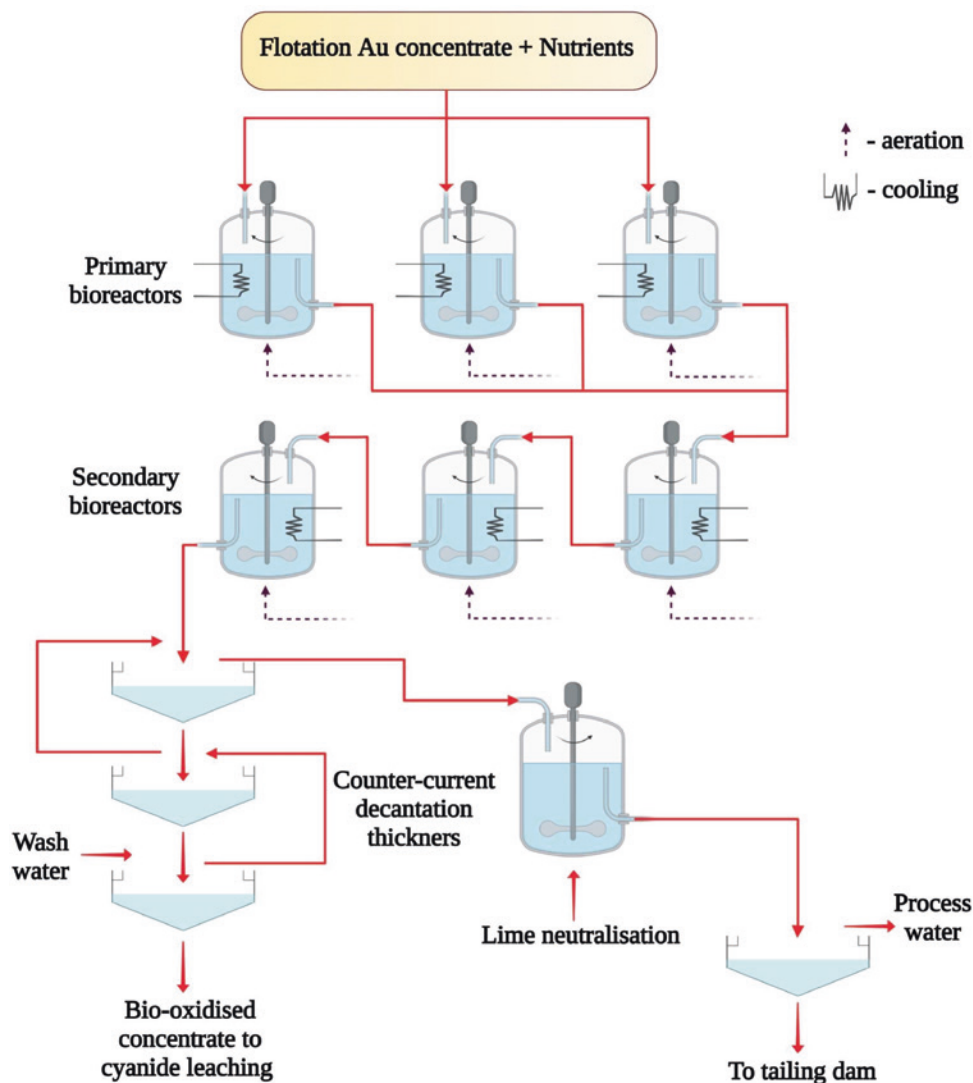


Figure 5 depicts an example flowsheet of the BIOX™ process. The flowsheet typically allows the processing of flotation concentrates with a 75-micron (80% passing) particle size to ensure adequate reaction kinetics along with a recommended 6% sulphide concentration for adequate bacterial activity (van Aswegen et al., 2007). Although further milling may improve Au recovery, finer feeds may also yield negative impacts in the downstream processes due to increased viscosity of the slurry and settling footprints. The milled feed concentrate is mixed with nutrients (i.e., nitrogen, phosphorus and potassium at 1.7, 0.9 and 0.3 kg per tonne, respectively) for microorganism growth (i.e., *Acidithiobacillus ferrooxidans*, *At. thiooxidans* and *Leptospirillum ferrooxidans*, further details in Smart et al. (2017)) and later introduced into three primary BIOX™ reactors arranged in parallel. The total residence time of the process is 4–6 days; the primary reactors account for half of that time to allow for sufficient microorganism growth. A minor fraction of CO<sub>2</sub> is also required for microorganism growth, and carbonate-lacking concentrates require adding limestone/CO<sub>2(g)</sub> to the primaries. Once microbial growth is

established, the overflow of the primary reactors is sequentially treated in secondary reactors with shorter (~1 day) residence times. All secondary reactors are equipped with cooling coils: sulphide oxidation is highly exothermic (Sect. 2.3), and cooling is imperative to regulate the bioreactor conditions to a temperature range of ~30–45 °C for the mixed mesophilic cultures in the BIOX™ process (Brierley, 2008). Moreover, air injection maintains DO at 2 mg/L, and pH is typically kept at 1.2–1.8 (van Aswegen et al., 2007). The oxidation process creates significant loads of dissolved ions and counter-current decantation (CCD) units are employed to reduce these loads before the cyanidation of the final concentrate. The resulting CCD overflow of this process contains Fe and As that require elimination or neutralisation (typically multi-stage—Broadhurst (1994)), whereas the thickened ore product is introduced to the cyanidation step.

Another case study is presented by Mintek and BacTech, who jointly developed the Au recovery technique BACOX™ at the Beaconsfield gold mine (now owned by NQ Minerals), Tasmania, Australia. The Au extraction at

**Fig. 5** Schematic overview of the flowsheet of the BIOX™ process. The milled flotation underflow is introduced into the primary (parallel) and secondary (serial) reactors to oxidise Au occluding ore gangue. The oxidised product is washed in the CCD unit; overflow: enriched solution of contaminants such as Fe and As is sent to waste processing, and underflow: Au recovery circuit through cyanidation (adapted from van Aswegen et al. (2007))



the mine has taken place intermittently (i.e., 1877–1914 and 1999–2012) and has produced nearly 1,800 kilo-ounces since 1877 (NQ Minerals, 2021). The BACOX™ process included six reactors, three of them as primaries. The gold ore went through a rigorous crushing, milling and flotation circuit, resulting in a feed size of 75 microns (i.e.,  $d_{80}$ ) with a throughput of 2.1 tonnes per hour. Subsequently, the processed ore was introduced to primary bioreactors (volume 365 m<sup>3</sup>), which were regulated at 37–43 °C and contained consortia of mesophilic bacteria (similar to BIOX™; Chingwaru et al. (2017)). The residence time for the entire process was ~6 days, and pH values were reported in the range of 1.0–1.4 (Neale et al., 2000). Interestingly, the BACOX™ process did not demand pH control because the deployed bacteria required low pH operations and high Fe concentrations (Neale et al., 2000). Following the biooxidation of the Au ore, the residue was thickened and subject to

cyanidation. The Beaconsfield mine reported recoveries of 16–20 g of gold per tonne in the earlier stages (Neale et al., 2000), and by the end of 2012, the average gold recovery was 10.5 g per tonne (NQ Minerals, 2021). Due to these promising results, a new plant is expected to be commissioned in 2022, according to Giles (2021).

## 4.2 Copper Industry

Despite Cu being the most biometallurgically produced metal in the world, bioreactors are not readily the first choice for Cu processing. Biometallurgy competes against other well-established Cu recovery techniques, e.g., pressure oxidation leaching—which may offer faster reaction kinetics and better economics—even though heap bioleaching is increasingly accepted as a viable Cu ore processing

technique (Ghorbani et al., 2016; Schlesinger et al., 2011). There are also advances in the development of bioreactors for Cu processing.

BHP Billiton developed a demonstration-scale bioreactor technology, BioCOP™ (Fig. 6), to treat chalcopyrite ore in the Alliance Cu plant in Chile (Dreisinger, 2006). Production was scaled at 20 kilotonnes per annum (ktpa) from a 77 ktpa Cu concentrate (Havlík, 2008). The process scheme largely resembled that of the BIOX™ process, except for the use of oxygen instead of air (Batty & Rorke, 2006; Dreisinger, 2006, 2016). In addition, thermophilic bacteria (e.g., *Acidimicrobium ferrooxidans*, *Sulfobacillus acidophilus*, *Sulfolobus metallicus*; Clark et al. (2006)) were employed to oxidise chalcopyrite at temperatures of 65–80 °C (Dreisinger, 2006, 2016). The process housed six bioreactors at 1260 m<sup>3</sup> each, a re-grinding circuit, as well as pre-leach, decantation, and filtration units, a pregnant leach solution storage and one of the world's largest agitators (Batty and Rorke (2006)). The primary reactors performed with >80% oxygen utilisation, reflecting the process's

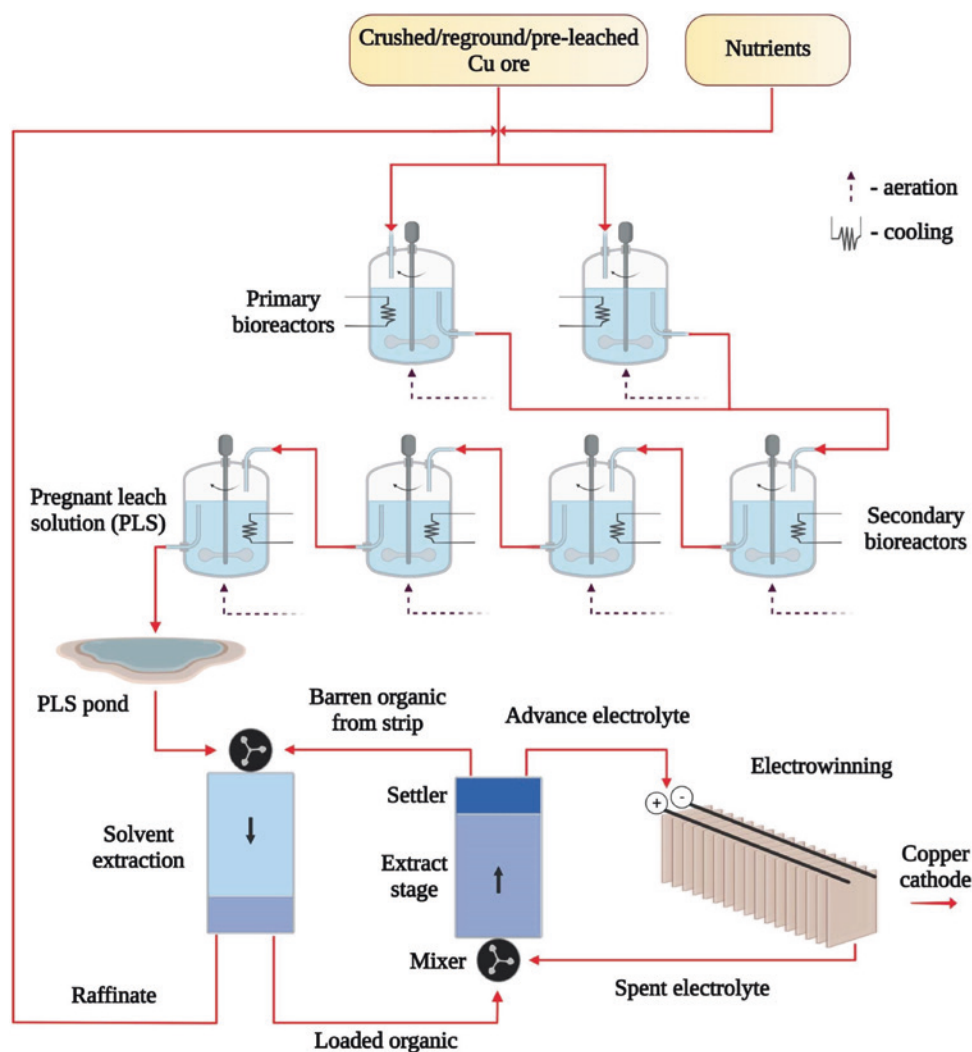
success at this site (Batty & Rorke, 2006). At this plant, thermophiles presented a significant edge over mesophiles (30–60% recovery) at high concentration chalcopyrite ore that otherwise required very fine milling (Dreisinger, 2016). Consequent to several bench-scale investigations, a prototype Cu plant of 20,000 tonnes per annum (tpa) was successfully operated for 18 months in 2004 and 2005 (Domic, 2007), albeit discontinued due to high operational costs (Knuutila, 2009).

### 4.3 Nickel and Cobalt Industry

Nickel (Ni) and cobalt (Co) are essential metals in high demand. Even though reported industrial applications of bioreactors for Ni or Co extraction are relatively scarce, biometallurgy is considered a viable option for extracting these metals.

Mondo Minerals assessed a bioreactor technology for recovering Ni and Co from a flotation concentrate based

**Fig. 6** Schematic overview of the flow sheet of the BioCOP™ process. The process follows a similar route to BIOX™ (Fig. 5), except for collecting the PLS for further processing. The PLS is introduced to the solvent extraction circuit, where a suitable organic solvent is employed to extract Cu. The loaded organic solvent is stripped and transferred to electrowinning. Here, the Cu cathodes are produced, and the rest of the solution is recycled. *Note* the same schematic can be used to recover any other base metal (e.g., Ni, Co) by selecting a suitable organic solvent in the solvent extraction step (modified after Batty and Rorke (2006) and Dreisinger (2006))



on Mintek's biotechnology at their mine sites in Finland (Gericke, 2015). Mondo commenced this project as a route to value-addition for talc mining by-products (Neale et al., 2017). Ni was the main target metal of interest, and the consideration for biometallurgy was partly triggered by high As concentrations (2.18% w/w) in the ore concentrate. The process included pre-processing the feed concentrate ( $d_{80}=20$  microns) through magnetic separation, subsequently introducing it to the bioreactor circuit, which encompassed seven tanks. Three tanks were designated primary reactors arranged in parallel, whereas four secondary reactors were placed in series. Every tank was equipped with cooling, airflow and  $\text{CO}_2$  supply to accommodate the moderate thermophiles (e.g., *Acidithiobacillus ferrooxidans*, *At. caldus* or *Leptospirillum ferrooxidans*; Venho (2012)) employed for the bioleaching at reactor temperatures of  $\sim 45^\circ\text{C}$  and pH values around 1.7 at both the primary and secondary reactors (Neale et al., 2017). The experimental-scale reactors demonstrated encouraging Ni and Co recoveries  $>95\%$ . Construction of a commercial-scale plant immediately followed and is expected to produce 1000 tonnes of Ni (and some Co) annually from a 12,000-tonne concentrate (Gericke, 2015). The sequential development of this Finnish plant at the Vuonos site is well-documented in Neale et al. (2017).

An example of biometallurgical Co recovery is presented by the Kasese pyrite mine in Uganda (BRGM (France)), which housed a bioreactor designed to process waste stockpile material. The initial mining activities from 1956 to 1982 focused on the extraction of Cu, which generated a pyrite-rich waste-concentrate (1.38% w/w Co) containing approximately 11,300 tonnes of Co (Morin & d'Hugues, 2007). BRGM initiated a bioreactor facility in 1998 that included circuits for milling, sizing, thickening, heat control, limestone addition, filtration, solvent extraction and electrowinning. The feed particle size was maintained at  $<35$  microns (i.e.,  $d_{80}$ ) at a rate of 240 tpd (Morin & d'Hugues, 2007; Schippers et al., 2014). The bioreactor circuit was composed of 5 tanks (each with  $1380\text{ m}^3$  volume) classified as primary, secondary and tertiary. Three tanks in parallel were assigned for the primary stage and two other tanks for each subsequent stage. The average temperature of all tanks was  $42^\circ\text{C}$  with pH values of 1.4–1.7 across the primary and secondary/tertiary stages (Mahmoud et al., 2017). Regarding performance, the primary stage reported Co recoveries of 60%, and the secondary/tertiary stages reported 20–30% (Morin & d'Hugues, 2007). The plant operated until 2014 and produced an average of 800 tonnes of Co per year (Schippers et al. (2014)).

While metallurgical bioreactor applications remain dominated by a few widely employed techniques (e.g., Au biooxidation), the selected industrial case studies discussed in this section and many others, as illustrated in Fig. 4,

highlight the diverse potential applications for bioreactor technology. Although a detailed comparison of such reactor performances is of marked importance, it is worth noting the complexity of such analysis. In particular, these performance parameters may drastically vary depending on numerous intricacies, such as locality, geology, mineral type, gangue associated, microorganisms, energy consumption and mineral processing circuits (e.g., comminution and flotation) to name a few. Therefore, it is challenging to set a fixed framework to present an assessment of the reactor operations for different mineral commodities.

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## 5 Opportunities and Future Directions

### 5.1 Emerging Bioreactor Initiatives

The commencement and success of any mining project are contingent on the socio-economical context and investment opportunities. Critical factors that affect commercial decisions for implementing bioreactor technologies at an industrial scale include commodity price, operating and capital costs of new processing facilities, as well as deposit-specific challenges for metal beneficiation. Bioreactor technologies for Au recovery have shown great success:  $>25$  million ounces of Au have been produced in the last 30 years through the various BIOX™ plants worldwide (Metso Outotec, 2021). The simplicity of the BIOX™ design results in relatively low operating costs and makes it economically competitive with other technologies (van Aswegen, 2007). Furthermore, high commodity prices have recently encouraged the development of new bioreactor projects in the Au industry. In contrast, only a few technologies have reached industrial-scale operation in the base metal industry (Fig. 4).

The capital cost of developing new facilities is a significant impediment to launching tailor-made bioprocessing facilities. Still, bioreactor technologies may have advantages in specific scenarios, and initiatives continue to emerge. BacTech is seeking investments for their 50 tonnes per day biooxidation plant in the Ponce Enriquez project (Ecuador), reporting initial experimental Au recovery at  $\sim 96\%$  (BacTech, 2021). The Beaconsfield project is anticipating production in early 2022, reporting promising gold grade estimates at 10.3 g/t, leading to 483,000 oz of gold using bacterial oxidation circuits (Giles, 2021, NQ Minerals, 2021). Further, RioZim, Zimbabwe, has prioritised a US\$ 17 million BIOX™ plant at the Cam and Motor mine to process Au ore (The Herald, 2021). Finally, Torres (2021) reports that the Coricancha mine and associated Tamboraque bioreactor plant in Peru are expected to commence processing Au and Ag within years.

## 5.2 Novel Technologies

Various aspects of hydrometallurgical bioprocesses remain not fully understood, and scientific insights continue to contribute to the further development and application of bioreactor techniques in the industry. For instance, advances in bioengineering and molecular biology allow for genetically engineered microorganisms to be used in biometallurgical technologies (Gumulya et al., 2018), particularly for materials from complex ore deposits or with considerable levels of contaminant impurities (Mahajan et al., 2017). Many microorganisms in acidic environments are yet to be cultured (Brune & Bayer, 2012), and establishing an engineered microbial consortium may require specialised control and monitoring of leaching or oxidation conditions. The ability to control growth conditions in bioreactors beyond what is achievable with ambient operations, e.g., heap leaching (Kaksonen et al., 2020a, 2020b), gives bioreactors a clear advantage. In addition to metal recovery from ore deposits, bioreactors have also been deployed for mine waste management applications, e.g., for the passive treatment of acid mine drainage (AMD) and recovery of residual metal fractions from waste rock and tailings materials (Bailey et al., 2016; Fernando et al., 2018; Habe et al., 2020; Santos & Johnson, 2018; Yildiz et al., 2019). Bioreactors are also being examined to recover critical elements such as Li, Co, In and REEs from mining and even electronics waste (Arshadi et al., 2021; Erust et al., 2021; Hubau et al., 2019, 2020). The operating conditions of such specific applications will vary widely, but bioreactors and the involved microbial consortia have the potential to be tailored to these various requirements.

Bioreactors might even find applications beyond Earth. In pursuit of exploring extra-terrestrial mineral resources, space biomineralisation has become an active field of research (Abbasi et al., 2021; Gumulya et al., 2022; Santomartino et al., 2022). Bioreactors were designed to perform bioleaching of REEs and vanadium from basalt rocks at the International Space Station (ISS) under different gravity conditions (e.g., microgravity, Mars' gravity, and Earth's gravity) with different bacterial species (*Sphingomonas desiccabilis*, *Bacillus subtilis* and *Cupriavidus metallidurans*) (Cockell et al., 2020, 2021). A testimony to the wide range of applications of metallurgical bioreactors, the extreme conditions found in space (irradiation, temperatures, oxygen availability) appear to not prevent the successful operation of bioreactors (Santomartino et al., 2022) despite the high costs and engineering challenges that remain (Klas et al., 2015).

Finally, industrial bioreactor facilities generally include multiple unit processes that require centralised communication systems to regulate the complex flowsheet. The adoption of Industry 4.0 (Fourth Industrial Revolution)

technologies—including cloud services, big data, Internet of Things (IoT) and AI (Dalenogare et al., 2018)—can catalyse the transformation of process plant data to digital platforms. This will allow more effective maintenance, control, simulation and waste management through intelligent decision-making (Flevaris & Chatzidoukas, 2021; Gorecky et al., 2014; Vaidya et al., 2018). Due to the increased availability of diverse and large volumes of (historical) data and the increasing ease of data cleaning and curation, the incorporation of Industry 4.0 is an important emerging venue for bioreactor projects (Pereira et al., 2017; Qin et al., 2016).

## 6 Concluding Remarks

This chapter discussed important aspects of bioreactor design and operation for metallurgical applications. We presented a selection of bioreactor projects to illustrate the wide range of bioreactor applications in the metal extractive industry. While metallurgical bioreactors are currently mostly used in specific industries (e.g., for Au recovery), the technology is actively pursued for various other (base) metal projects. The prospects are promising for bioreactor-based hydrometallurgy, with exciting developments in microbiology, sensors, big data integration, among others, expanding the already wide range of potential applications. Bioreactors can have significant advantages over alternative extraction techniques, including process efficiency, controllability and environmental stewardship. As a result, they will likely play an essential role in the metal supply chain for decades.

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