Oxidation Behaviour and Bio-oxidation of Gold-bearing Sulphide Ores: Oxygen Capabilities and Challenges*

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Abstract

The paper presents an overview of bio-oxidation of sulphidic refractory gold ores prior to gold cyanidation. This review discusses several factors, more importantly, oxygen requirements and oxygen limitations in biological oxidation of various sulphide minerals associated with gold ores. The availability of sufficient oxygen in bio-oxidation systems can speed up and enhance the oxidation of sulphide minerals, allowing the gold to be liberated for further extraction. However, oxygen supply and its low solubility in water have been the major limiting factors in bio-oxidation processes. More importantly, oxygen limitations are found to affect the rate of sulphide oxidation and the volume of materials that can be treated for gold leaching. First, the paper discusses the influence of dissolved oxygen on the oxidation behaviour of various sulphide minerals found in refractory gold ores or concentrates. Further discussed are the limiting factors in relation to dissolved oxygen during bio-oxidation of refractory gold ores. This review demonstrates that oxygen availability is a major challenge and therefore, oxygen enhancement techniques or strategies are vitally needed. As well, the review serves to inspire new research into efficient strategies to enhance oxygen availability.

Keywords: Oxygen; Oxidation; Pretreatment; Sulphide minerals; Bio-Oxidation

1 Introduction

Gold extraction is becoming more challenging with the increasing number of gold deposits containing refractory sulphide and carbonaceous minerals, which generally limits the oxidative gold dissolution rates (Mpinga *et al.*, 2015; Nazari *et al.*, 2017; Asamoah *et al.*, 2018a; Kim and Ghahreman, 2019). Refractory gold ores or concentrates often include submicroscopic gold contained inside the crystal matrix of iron sulphide minerals, such as pyrite, pyrrhotite, and arsenopyrite (Fig. 1). In addition to refractoriness, the sulphide minerals or ions such as Fe^{2+}, S^{2+}, HS, react with oxygen and consume extra leaching reagents, which is a widespread problem (Saim *et al.*, 2022). Sulphide oxidation to polysulphide or elemental sulphur, polysulphide oxidation to elemental sulphur, and the conversion of short chain polysulphide to long chain polysulphide are all possible to consume dissolved oxygen (Breuer *et al.*, 2008; Zia *et al.*, 2019; Kim and Ghahreman, 2020). Overall, the presence of the sulphide minerals can potentially increase the cost of gold extraction by consuming more chemicals and potentially passivating the surface of gold particles, thereby reducing gold recovery (Brittan and Plenge, 2015). Hence, it is important to effectively pretreat these refractory materials.

It is necessary to first break down the host material using oxidative methods such as roasting, pressure oxidation, or bacterial oxidation in order to expose the gold, which can then be recovered by cyanidation. Pretreatment process choices vary in their application based on their efficacy, capital investment, and operational expenses, among other factors. Among these pre-treatment methods, bio-oxidation is regarded as a safer alternative that is used before cyanidation to enhance the leaching kinetics of refractory sulphide gold ores (Dufresne *et al.*, 1994; Deschênes *et al.*, 2003). However, the capital-intensive bio-oxidation process requires large amount of oxygen as a key reagent, as oxygen transfer rate is often the rate-limiting step in the bio-oxidation process. For instance, conventional bio-oxidation processes are limited to maximum pulp densities of 18-20% (w/v), and this is due to inefficient sulphide oxidation beyond these values.

To overcome all these pressing challenges, oxygen supply should equal or exceed the oxygen requirements in the bio-oxidation circuit. It is known that factors such as temperature, dissolved mineral solutes and pulp density significantly affect oxygen solubility and thus, its availability in solution becomes limited. The paper presents an overview of sulphidic refractory gold bio-oxidation process prior to gold cyanidation. First, this paper discusses the influence of oxygen on the oxidation behaviour of various sulphide minerals found in refractory gold ores or concentrates. Afterwards, several factors relating to oxygen requirements and oxygen limitations in the biological oxidation of various sulphide minerals associated with gold ores are discussed.

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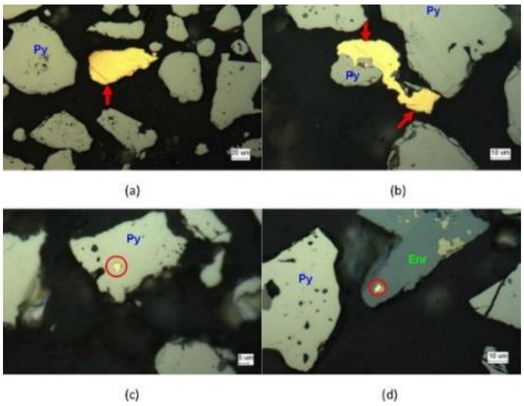

Fig. 1 shows the occurrence and the association of gold found in the concentrate. (a) fully liberated gold particle with pyrite particles (b) gold grain associated with pyrite, (c) gold locked in pyrite (d) gold locked in enargite matrix (Ahn *et al.*, 2019)

2 Influence of Dissolved Oxygen on the Oxidation Behaviour of Sulphide Minerals

The cyanidation process has been effective in leaching free milling gold ores, while the sulphide refractory ores have proven difficult for conventional cyanide gold dissolution (Khalid *et al.*, 2018; Khalid and Larachi, 2018; Yang *et al.*, 2020). This widespread problem has continued to increase as free milling gold deposits gradually deplete (Khalid and Larachi, 2017). Sulphide minerals cause a significant consumption of oxygen in cyanide solution, and this reduces the amount of dissolved oxygen available for oxidative gold leaching (Soltani *et al.*, 2020). Besides, it is revealed that the dissolution of the sulphide minerals forms a passivation layer of sulphides, arsenic or iron compounds on the gold surface. The extent of sulphide mineral dissolution depends on the type of sulphide mineral and the amount of dissolved oxygen present. The effect of dissolved oxygen level on pyrite oxidation is illustrated in Fig. 2 (Feng and Van Deventer, 2003; Cama *et al.*, 2006).

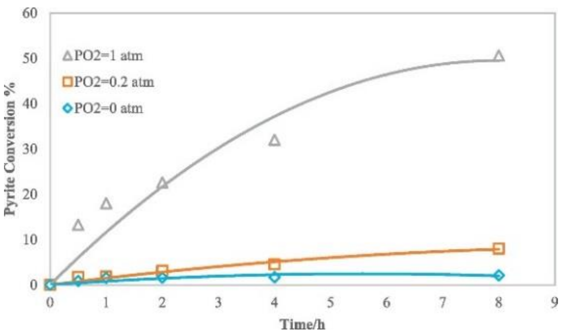

Fig. 2 Effect of oxygen partial pressure on the oxidation of pyrite and arsenian pyrite (Bidari and Aghazadeh, 2018)

Sulphide minerals are highly reactive in alkaline cyanide solutions, making gold cyanidation in sulphidic ores demanding excess cyanide and oxygen consumptions (Azizi *et al.*, 2014). In aerated cyanide solutions, most sulphide minerals are known to exhibit dissimilar rest potentials. In order to understand how various sulphide minerals influence the dissolution kinetics of gold in air-saturated and oxygen-enriched cyanide solutions, extensive studies have been carried out. It is demonstrated that both the solubility of the various sulphides and the oxygen concentration in solution determines the leaching behaviour of gold. Gold dissolution during cyanidation can be enhanced or diminished, depending on the type and the concentration of dissolved oxygen, as the degree of sulphide decomposition varies with oxygen concentration (Kim and Ghahreman, 2019). For instance, while galena, stibnite and chalcocite caused a decrease in gold dissolution rate, some sulphide minerals, such as pentlandite, chalcopyrite, pyrrhotite, sphalerite, molybdenite, arsenopyrite and pyrite can increase the gold dissolution rate in the oxygen-enriched cyanide solutions (Fig. 3) (Liu and Yen, 1995). From a similar observation, various concentrations of sulphides including pyrite, pyrrhotite, chalcopyrite, realgar and arsenopyrite on gold dissolution in cyanide media was examined under constant experimental conditions. Variations in gold dissolution rate with the sulphide minerals decreased according to the following order: realgar > pyrrhotite > chalcopyrite > pyrite > arsenopyrite (Deschênes *et al.*, 2002).

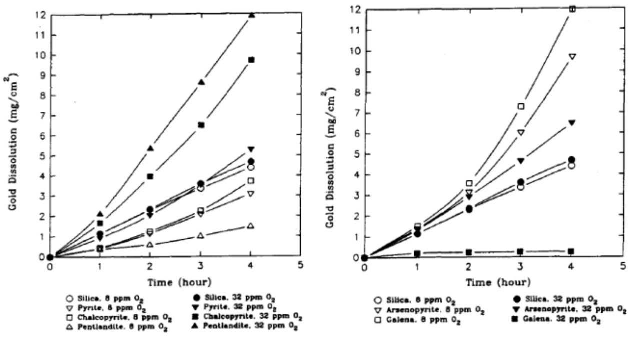

Fig. 3 Effects of pyrite, chalcopyrite, pentlandite, arsenopyrite, galena and oxygen on gold dissolution (Liu and Yen, 1995).

In a rotating disc electrode experiment, the presence of chalcopyrite reduced and enhanced the dissolution activity of pure gold in low and high potential regions, respectively (Yang *et al.*, 2020). From another study, the leaching behavior of a gold disc electrode successively immersed in slurries of industrial ore and its major sulphide constituents (pyrite, sphalerite and chalcopyrite) was monitored. The inhibiting effect on gold leaching decreased in the order of chalcopyrite > sphalerite > industrial ore > pyrite (Azizi *et al.*, 2010). However, there was an improvement in the gold leaching rate after pre-oxidation of the industrial sulphide ore prior to cyanidation. Additionally, no beneficial effect of pre-oxidation on gold leaching was observed for the major sulphide ore constituents in separate testing, even though there was obvious reductions in cyanide consumption (Azizi *et al.*, 2010).

Oxygen in the leaching step increases the rate of gold dissolution, in some cases enhances the final gold recovery and is often accompanied by savings in cyanide, especially when oxygen is used during pre-oxidation. Due to the extra surface area available for oxygen reduction in aerated cyanide solutions, sulphides dissolution rate increases when sulphides are electrically in contact with gold (Huai *et al.*, 2019). For example, in the absence of complicated agents, galvanic current measurements were used to study gold and pyrite galvanic interaction under ambient and oxygen-enriched circumstances. Fig. 4 shows that when gold is present and in contact with pyrite under oxygen-enriched conditions, the oxidation rate on the pyrite increased. This enhancement is due to a significant increase of potential difference under the oxygen-enriched conditions. A high amount of surface area is provided by gold, which facilitates cathodic reactions, particularly when oxygen is bubbled through the solution. In essence, due to the fact that gold has a higher oxygen reduction activity in aqueous solution, it can remove the electrons from oxygen to continue the high rate of pyrite oxidation (Huai *et al.*, 2018; 2019). Due to its greater rest potential, pyrite charge carriers would find a more favorable energy on gold surface in the presence of oxygen, as shown in the magnified dashed square in Fig. 4 (Huai *et al.*, 2018).

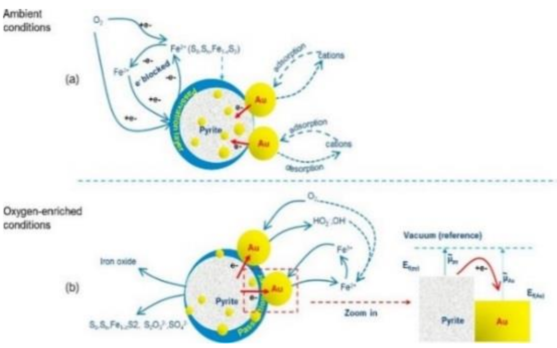

Fig. 4 Schematic diagrams of galvanic interactions between pyrite and gold under ambient and oxygen-enriched conditions (Huai *et al.*, 2018).

Hence, this enhanced sulphides dissolution in the presence of gold and oxygen-enriched environment accelerates gold liberation to increase the accessibility of leaching reagents. In effect, the amount of gold that can be extracted from refractory sulphide ores depends on the degree of sulphide oxidation as shown in Fig. 5 (Spasova *et al.*, 2017; Ahn *et al.*, 2019; Wu *et al.*, 2020). In the presence of soluble sulphide minerals, however, the leaching behavior of gold is quite complicated since the formation of sulphide ions in solution results in the passivation of the dissolution of gold when enough oxygen is not present (Dai and Jeffrey, 2006).

Aside passivation of the gold surface, one of the main mechanisms for loss of gold in sulphide gold ores is the destabilisation of gold cyanide complex by sulphur metastable species such as hydrosulphide, polysulphide, thionates, sulphite. The destabilisation of gold cyanide by elemental sulphur and sulphide ion is through two different mechanisms of precipitation of AuCN and thiocyanate formation as well as reduction of gold by formation of sulphite and sulphates, respectively. Although the addition of lead nitrate can decrease the inhibiting effect of sulphide ions by formation of lead sulphide, lead cannot eliminate the negative effect of elemental sulphur (Deschênes and Wallingford, 1995; Zia *et al.*, 2019; 2020). Therefore, to significantly overcome the adverse impact of sulphur species on the stability of gold cyanide complex, sufficient oxidation of sulphur species is required (Deschênes and Wallingford, 1995; Zia *et al.*, 2019; 2020).

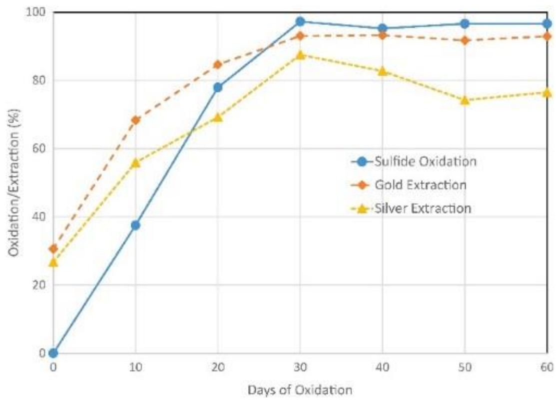

Fig. 5 Sulphide oxidation and gold/silver extraction from concentrate bio-oxidation (Ahn *et al.*, 2019).

Furthermore, it is revealed that the particle sizes of sulphide minerals and their concentrations have significant impact on gold dissolution (Bas *et al.*, 2018). The oxidation of these sulphides present is often desirable to liberate the gold, however, significant detrimental effects of sulphides can be observed when their concentration is about 20% or more (Deschênes *et al.*, 1998; Guo *et al.*, 2005). Moreover, existence of several physicochemical behavior and interactions of sulphidic refractory gold ores demand careful investigations to ensure efficient gold extraction. Thus, because of the many synergetic and anti-synergetic galvanic interactions manifesting between the different mineralogical phases present in gold ores, multi-sulphidic gold ores cyanidation pretreatment strategies based on mono-sulphide mineral phases cannot be fully reliable in understanding and predicting the efficiency of pre-oxidative treatment (Azizi *et al.*, 2014; Crundwell, 2014; Kim and Ghahreman, 2019). Suggestions are that high sulphide containing ores should be given adequate pretreatment to fully or partially break down the sulphide matrices to liberate gold, followed by gold leaching under oxygen atmosphere.

3 Bio-oxidation

Increasingly used in heap, dump and in situ leaching, bacterial oxidation of sulphide minerals has acquired industrial significance in recent years (Seifelnassr and Abouzeid, 2013; Chen *et al.*, 2017; Kaksonen *et al.*, 2018; de Carvalho *et al.*, 2019). Sulphide ores, particularly gold-bearing refractory ores and concentrates, are commonly pretreated with bio-oxidation methods (Loayza *et al.*, 1999; Kaksonen *et al.*, 2014; Kanayev *et al.*, 2016; Marchevsky *et al.*, 2017). Bio-oxidation of sulphide minerals relies on bacterial oxidation of Fe^{2+} to Fe^{3+} from a practical point of view, and in stirred tank bioreactors, this occurs ideally, whereas in heaps and dumps, it occurs less intensely. Generally, treatment of gold-bearing sulphide concentrates by bio-oxidation employs acidophilic microorganisms that oxidize the ferrous iron and sulfur. Bio-oxidation of sulphide minerals begins with ferric iron breaking down the crystal lattice surface connections, and the sulphides, ferrous iron and trivalent arsenic (for arsenopyrite) are more easily dissolved by cyanide and oxygen (Ofori-Sarpong *et al.*, 2013; Fomchenko and Muravyov, 2014; Asamoah *et al.*, 2018b). When it comes to extracting sulphide minerals from refractory gold concentrates, bio-oxidation technology is more environmentally friendly (Zheng *et al.*, 2018), and are able to treat gold-bearing sulphide ores or concentrates with double-refractory properties with high efficiencies (Amankwah *et al.*, 2005; Bulaev *et al.*, 2015).

Generally, the conventional technology for bio-oxidation of refractory sulphide concentrate requires 4 to 6 days, which limits its efficiency (Ahmed and El-Midany, 2012; Fomchenko *et al.*, 2016). The heap bio-oxidation method, for example, takes over 80 days to achieved efficient gold recovery (Roberto, 2017; Li, Tong, *et al.*, 2020; Li, Zhong, *et al.*, 2020). For instance, it took 15 days of bio-oxidation to extract the maximum amount of iron using a mixed culture of moderately thermophilic microorganisms with a pulp density of 5% (w/v) (Abdolahi *et al.*, 2017). This is due to the fact that partial or incomplete sulphide oxidation can lead to high consumption of reagents such as oxygen and cyanide during cyanidation, and consequently yield lower overall recovery, as commonly encountered in bio-oxidation of refractory ores (Ofori-Sarpong *et al.*, 2020; Khamidov *et al.*, 2021). As such, several strategies have been adopted to improve the bio-oxidation process, including the use of mixed microorganism cultures (Ciftci, 2011; Zaulochnyi *et al.*, 2011; Ciftci and Akcil, 2013;Wang *et al.*, 2016; Lorenzo-Tallafigo *et al.*, 2019; Sedelnikova *et al.*, 2019; Bulaev *et al.*, 2019), two-stage bio-oxidation (Zaulochnyi *et al.*, 2011; Fomchenko and Muravyov, 2014; Muravyov, 2019), application of pressure (Hajdu-Rahkama *et al.*, 2019) and the use of metal cations (Deng *et al.*, 2000; Zhang *et al.*, 2016; Hu *et al.*, 2017; Zhang *et al.*, 2021). These strategies are mostly carried out to ensure high or almost complete sulphide oxidation in the bio-oxidation process.

3.1 Dissolved Oxygen in Bio-oxidation

In bio-oxidation, oxygen is very essential to achieve maximum sulphide oxidation. Dissolved oxygen (DO) is used by bio-oxidation microorganisms as an electron acceptor for the oxidation of reduced sulfur and iron. It is known that ferric iron (Fe^{3+}) can be utilized to enhance sulphide oxidation rates, as a low-cost oxidant (Vera *et al.*, 2013; Hubau *et al.*, 2018; Deng *et al.*, 2020). However, it is reported that dissolved oxygen can lower the Gibbs free energy of the sulphide oxidation process far easier than using Fe^{3+} ions as the only oxidant (Song *et al.*, 2018). Yet, a key difficulty in bio-oxidation systems is oxygen supply and availability, especially with high sulfur loadings. This is due to low oxygen solubility in water, and as a result, large quantities of air are constantly required, which is technically challenging and adds to the expenses. When it comes to calculating capital and operational costs, aeration of slurries is crucial especially for arsenic-bearing refractory gold ores. As a result, the design of reactors, air introduction methods, power input and optimization of operating parameters to achieve the required oxygenation are all the subject of much study (Maier and Büchs, 2001; Loi *et al.*, 2006; Shen *et al.*, 2021). The downside is that these alternatives would result in an increase in energy usage and cost.

On the other hand, oxygen transfer constraint owing to lower oxygen solubility at higher temperatures is a substantial process issue that cannot be solved by merely raising agitation speeds and aeration rates under thermophilic bacteria environment. Because of this, the oxygen solubility in thermophilic systems can be reduced by one-third compared to mesophilic conditions (Mahmoud *et al.*, 2017).

In moderate and low-temperature operations, air is generally selected because of technical and cost restrictions. Nonetheless, because of the oxygen content of air (20.9% O_2), there is a limit to how much aeration is needed in the bioreactors. Nonetheless, the use of enriched oxygen in such reactors on a wide scale also comes with its own set of benefits and problems. Research done on the impacts of DO on the cellular and molecular level indicate that oxygen uptake rate, Fe^{2+} oxidation activity, and *rus* gene expression of *A. ferrooxidans* all increased with DO concentration. For example, while the bio-oxidation process was limited at 1.2 mg/L DO level, higher DO content resulted in higher bio-oxidation and cell growth rates (Sun *et al.*, 2012a). More so, higher DO concentrations result in shorter bacteria exponential growth phase. It is thus, inferred that the cell development can be slowed down at lower levels of oxygen (Sun *et al.*, 2012b). It is indicated that during the initial stages of oxidation, the cell concentration clearly benefits (Cheng *et al.*, 2021). Furthermore, *A. ferrooxidans* bio-oxidation is illustrated in Fig. 6 by the relationship between DO concentration and oxygen uptake rate. Oxygen uptake rate rose throughout the exponential phase of bacterial growth, peaked in the late stages of cell growth, and then declined when the cells began to die and metabolism slowed (Sun *et al.*, 2012b).

There is a significant rise in bio-oxidation efficiency in the beginning followed by a decline in efficiency as DO levels continue to increase. It is related to the fact that as DO levels increase, the amount of reactive oxygen species within the bacterial cells also increase considerably. Under oxygen-enriched conditions, increasing the initial Fe^{2+} concentration reduces the oxidative activity of the microbial community in the beginning and increases it later, as the content of reactive oxygen species increases, and cell growth can be inhibited throughout the process, resulting in a decrease in bio-oxidation efficiency (Wang *et al.*, 2016). From another investigation, a high Fe^{2+} content at the beginning of the experiment was found to be the only factor that had any influence on the cell growth rate (Zabihollahpoor and Hejazi, 2018).

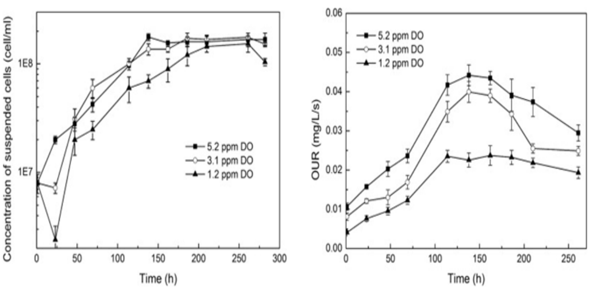

Fig. 6 Evolutions of the suspended cell concentration and oxygen uptake rate at various DO concentrations during the bio-oxidation (Sun *et al.*, 2012b).

DO effect can vary according to the type of bacteria community employed. From a study using Leptospirillum ferriphilum-like bacteria and *Sulfobacillus thermosulfidooxidans* as the dominate strains, when DO levels increased, the relative proportions of Leptospirillium ferriphilum-like bacteria in the bacteria community initially increased and subsequently dropped, while *Sulfobacillus thermosulfidooxidans* displayed the reverse trend (Wang *et al.*, 2015). However, it was also discovered that when DO levels increased, bio-oxidation efficiency initially improved and then declined, while reactive oxygen species concentrations increased in bacteria (Wang *et al.*, 2015).

There is a system parameter that indicates the critical value of the volumetric oxygen transfer coefficient, which corresponds to the lowest and highest amount of aeration needed in bioreactors to sustain substrate oxidation without oxygen constraint (Myerson, 1981). Determining this system aeration conditions has practical and economic implications since the rate of aeration plays an important influence in the cost of bio-oxidation. For example, the effects of various DO concentrations studied in controlled batch *Sulfolobus* sp. cultures at 78 °C revealed that between 1.5 and 4.1 mg/L were determined to be the optimum DO concentration for iron oxidation, whereas ferrous oxidation rates were reduced by using higher DO concentrations (above 4.1 mg/L) (de Kock *et al.*, 2004). In another example, during ferrous iron and elemental sulfur oxidation process, the critical values of volumetric oxygen transfer coefficient needed to ensure oxygen-unlimited oxidation were 7.70 and 4.88 h^{-1}, respectively, in *Acidithiobacillus ferrooxidans* cultures (Mandl *et al.*, 2014). Generally, the iron oxidation activity of bacteria in the presence of finely powdered suspended sulphide minerals is negatively impacted by oxygen levels below 1–2 mg/L (de Kock *et al.*, 2004; Sun *et al.*, 2012a).

On the other hand, some studies revealed that the critical value above which the DO concentration is detrimental to the microorganisms is found to be much higher than the one usually mentioned. When the DO content in a bio-oxidation reactor was varied from 4 to 17 mg/L, there was an increase in the sulphide dissolution efficiency as the DO level increased from 4 to 13 mg/L (Guezennec *et al.*, 2017). The increase in oxygen transfer rate from the gas phase to the liquid phase was identified to be the cause of the improved bio-oxidation efficiency. However, microbial activity and oxygen consumption both reduced substantially at 17 mg/L of DO (Guezennec *et al.*, 2017). According to another similar study, results demonstrated that using oxygen-enriched gas did not reduce the bio-oxidation performance. Even at high solid load

(20% and more), high levels of dissolved oxygen (up to 14 mg/L) that were attained in the experiments had no detrimental effects on microorganisms (Guezennec *et al.*, 2016).

3.1.1 Influence of Pulp Density

Bio-oxidation medium containing finely powdered sulphide minerals at varying pulp densities are commonly used to test the influence of oxygen on bio-oxidation, since suspended particles (along with attached bacteria) provide further obstacles to oxygen transport. There has been a linear relationship between solids content and bio-oxidation rate when the oxygen supply is not limited. Nevertheless, as solids concentration increases, the bio-oxidation rate decreases due to oxygen limitation (Bailey and Hansford, 1993, 1994; Shen *et al.*, 2021). As such, the bio-oxidation of refractory gold-bearing sulphide concentrates has been restricted to 18-20% solids concentrations, as opposed to the 40-55% that is commonly employed during gold leaching (Guezennec *et al.*, 2017; Rodrigues *et al.*, 2021). This is so because when solids concentrations are high, oxygen availability has been recognized as a significant limiting factor in the bio-oxidation process.

In particular, data indicates less gold recovery from the oxidised ore with solids concentrations of 10 % and 20% (w/v) compared to 5% solids (w/v) because the degree of sulphide oxidation was reduced as the pulp density increased (Ciftci and Akcil, 2013). Furthermore, due to the presence of high sulphide minerals (concentrate containing of 56% of pyrite, 14% of arsenopyrite), bio-oxidation was not stable at a pulp density of 1.5:10 (solid to liquid ratio), whereas oxidation was found to be stable at a pulp density of 1:10, as shown by the liquid phase characteristics (Bulaev, 2019). Moreover, a significant increase in Fe release rate was reported when employing oxygen and carbon dioxide enriched air for the bio-oxidation of gold-containing pyrite material using mesophiles, *T. ferrooxidans*, moderate thermophile *Sulfobacillus acidophilus* and *Sulfolobus*. At varied pulp densities of 3, 10 and 20% (w/v), the bio-oxidation of pyrite under optimal gas enrichment resulted in near complete iron extraction. However, for experiments with thermophile *Sulfobacillus acidophilus* and *Sulfolobus*, the leaching rate dropped fast at high pulp densities, more so at 40% than 30% (w/v). Thermophile *Sulfobacillus acidophilus* and *Sulfolobus* trials were found to have low dissolved oxygen concentrations at 40% solids, indicating oxygen limitations in these two cultures (Witne, 2004). In another example, due to the low sulphide content of the tailings materials and easy adaptation the mesophilic microbe at even greater solid concentration, comparatively, greater pulp densities (20% solids (w/v)) during bio-oxidation allowed gold extractions of about 95% with less cyanide consumption (Rodrigues *et al.*, 2021).

3.1.2 Influence of Agitation

Generally, oxygen mass transfer rate is typically increased to guarantee that the DO concentrations remain higher than the limit concentration. Commonly, due to the low solubility of oxygen, the medium is agitated to improve oxygen transfer efficiency. However, aiming at maintaining cells and particles in suspension, liquid agitation can provide shear stress which can impair bio-oxidation response efficiency by killing cells that are susceptible to shear stress. The influence of agitation speed on the mineral bio-oxidation process continues to be debated, yet the mechanism is still unknown. A certain degree of stirring might impede the growth of bacteria and bio-oxidation. It has been shown that a greater shear stress on bacteria is present in the impeller region compared to the other locations, which tend to damage the cells during agitation (Zheng *et al.*, 2018).

Moreover, as a result of the greater agitation intensity, the suspended cells can be destroyed, and the cells prevented from adhering to the mineral surface. Thus, with bio-oxidation, choosing the right impeller design can be important to achieving the optimum solid dispersion within the tank, while maintaining minimal energy usage as well as minimum shear stress on particles (Chéron *et al.*, 2020). It is reported that at high pulp densities (30 and 40%) and optimal gas enrichment, the leaching rate decrease along with low metal dissolution and redox potential values, which are both attributed to shear stress resulting from cell attrition (Witne, 2004).

4 Conclusion

This review has highlight oxygen potentials and challenges during various gold pretreatment methods for sulphidic refractory gold ores. It has been shown that during gold leaching, the leaching rate and the amount of gold that can extracted significantly depends on the type of sulphide minerals association in the ore and the oxygenation conditions. Under oxygen-enriched conditions, the rate of gold dissolution can be unaffected, increased or retarded in the presence of different sulphide minerals. Perhaps most importantly, the sulphide minerals consume more oxygen and also passivate gold surfaces during leaching. Hence, pretreatment methods are required to ensure efficient oxidation sulphide minerals present.

Oxidation and dissolution of sulphide minerals require oxygen in the solution phase due to the numerous biological and chemical oxygen demand involved. Before efficient sulphide oxidation processes can occur, oxygen must be dissolved into a liquid media via gas-liquid mass transfer. For this requirement, the gas to liquid phase transfer must be at least as fast as or faster than the rate of demand in the solution phase. Crucially, pretreatment using bio-oxidation has been unable to operate at high pulp densities (limited to 18-20%), unlike the conventional gold cyanidation process, which operates at relatively higher pulp densities (40-55%). Despite significant efforts in research, the bio-oxidation process takes about 4-6 days to ensure successful sulphide oxidation. Thus, even though bio-oxidation is more environmentally friendly, it takes a longer period to complete the oxidation process, yields lower gold recoveries and it can only treat relatively small amount of materials. All these limitations mostly relate to oxygen limitations or oxygen volumetric mass transfer constraints within the system.

Generally, a rise in oxygen availability under these pretreatment conditions is typically made possible by increasing the aeration rate, increasing impeller agitation rate, and improving design of the agitator. However, cell shear stress damage to bio-oxidation microorganisms becomes a limiting issue at high agitation speeds, and power inputs in the face of high pulp densities and agitation speeds cannot be continuously increased to address oxygen mass transfer limitations. Innovative actions are still required in order to develop new techniques and oxygen enhancement strategies for sulphide minerals oxidation. It is also important that a comprehensive metallurgical test programs are performed to assess all process alternatives for different ores and concentrates to determine the best approach for high gold recovery.

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