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Redox-Mediated Bioleaching: Strategies for Improving Metal Recovery from Sulfide Minerals

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The global shift toward a green economy is increasing the demand for metals, but bioleaching remains limited by low efficiency. One of the primary reasons for this is mineral passivation, where reaction products form layers on mineral surfaces, slowing or stopping metal release. Studies show that redox potential (Eh) plays a key role at the interface between microbes and minerals and can strongly influence bioleaching performance [1]. In many bioleaching studies, efforts to maximize microbial growth unintentionally increase the redox potential to very high levels. Under such conditions, rapid formation of compounds like jarosite and elemental sulfur occurs [2]. These products create dense surface layers that block mass transfer, reduce contact between oxidants and the mineral surface, and lead to early termination of metal dissolution as described in equations (1-3) [2].

$MS + 2Fe^{3+} \rightarrow M^{2+} + 2Fe^{2+} + S^0$ (Eq. 1)

$2Fe^{2+} + 0.5O_2 + H^+ \rightarrow 2Fe^{3+} + H_2O$ (Eq. 2)

$S^0 + 1.5\ O_2 + H_2O \rightarrow SO_4^{2-} + 2H^+$ (Eq. 3)

Recent research highlights the importance of controlling the ratio of ferric to ferrous iron (Fe^{3+}/Fe^{2+}) to maintain an optimal redox range, often referred to as a “redox window,” that is better suited for different sulfide minerals. Acidophilic microorganisms such as *Acidithiobacillus* and *Leptospirillum* can adapt their metabolism under controlled redox conditions, allowing sustained and more efficient leaching [3]. Several strategies for active redox control have been explored, including regulation of aeration, use of galvanic interactions, and addition of catalysts such as silver ions or carbon-based materials. These approaches help lower the energy barrier for sulfide oxidation, particularly for difficult-to-leach minerals like chalcopyrite. By viewing bioleaching as a controlled redox-driven process rather than a passive outcome of microbial growth, it can be treated as a more precise and efficient electrochemical technology. Better control of redox conditions can overcome kinetic limitations and improve metal recovery from low-grade ores and mine tailings, which are increasingly important for future metal supply.

Keywords- Redox-controlled bioleaching, low-grade ore, sulfide minerals