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EXPLORING THE APPLICATION OF *ACIDITHIOBACILLUS FERROOXIDANS* FOR THE BENEFICIATION OF PLATINUM GROUP METALS-BEARING BASE METAL SULPHIDES

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Biotechnology has emerged as a promising alternative to existing minerals processing methods, offering potential advantages in terms of cost-effectiveness and environmental sustainability. One area where microorganisms have shown significant promise is in the leaching of metals from medium and low-grade sulphide minerals thanks to the metabolites they produce. Extensive research has been conducted on the utilization of microorganisms for mineral beneficiation, with a specific focus on Acidithiobacillus ferrooxidans. This paper provides a comprehensive review of the application of A. ferrooxidans in bio-oxidation and biohydrometallurgy, highlighting its potential to replace inorganic reagents in the flotation of precious metals (PGMs) that are associated with sulphide ores.

Keywords: Acidithiobacillus ferrooxidans, Biotechnology, sulphides, economically.

INTRODUCTION

The Bushveld Complex (BIC) located in South Africa and the Great Dyke in Zimbabwe are the only two distinct yet similar ultramafic layered intrusions that contain significant deposits of platinum group metals (PGMs) [1]. The primary economic concentrations of PGMs are typically found in the Merensky Reef, Upper Group 2 (UG2), and Plat reef. These reefs are renowned sources of various PGMs, namely platinum (Pt), palladium (Pd), rhodium (Rd), ruthenium (Ru), osmium (Os), iridium (Ir), and gold (Au). While PGMs are traditionally extracted from ores, their high value has led to the recovery of these metals from industrial residues with diverse compositions and qualities. Consequently, the development of innovative technologies for the extraction, recovery, and separation of PGMs holds significant importance. PGMs are mostly associated with base metal sulphides (BMS), tellurides, arsenides, PGMs alloys with silicates as gangue minerals.

Recently, there has been a noticeable decline in the availability of high-grade PGM ores, leading to the reduced economic viability and effectiveness of conventional PGM recovery methods [2,3]. Consequently, there is growing interest in the application of biobeneficiation techniques for PGMs, which offer the potential for improved economics, effectiveness, and environmental sustainability. Biometallurgy and biobeneficiation involve leveraging microorganisms and the compounds they produce to extract and enhance the value of valuable minerals. The integration of biotechnology into the mineral processing and metallurgical sector has witnessed a gradual increase over time.

This systematic review aims to investigate and outline the efficacy of *A. ferrooxidans* and their potential application in the processing of PGMs.

METHODOLOGY

A primary of a systematic review goal is to investigate the body of information to answer a set of research questions. Given the revolutionary advances and expanding improvements in the field of biomining, and with the depletion of high-grade ores, the employment of *A. ferrooxidans* in precious metals processes has gotten a lot of attention over the years. The potential application of *A. ferrooxidans* reviewed in this paper is forecasted based on the PGMs minerals association. The research questions driving this research were as follows:

1. How is *Acidithiobacillus ferrooxidans* applied in the hydrometallurgical processing of PGMs-bearing sulphides?
2. How *Acidithiobacillus ferrooxidans* be applied in PGMs-bearing sulphides concentration processes?

DISCUSSION

This section addresses the synthesized data from the existing literature which was done with the aim of addressing the research questions.

The chart above shows the rate at which *A. ferrooxidans* is applied in different metallurgical processes based on the reviewed articles. The use of these bacteria in hydrometallurgy was categorized into biooxidation and bioleaching. Bio-oxidation was mainly used in gold pro-

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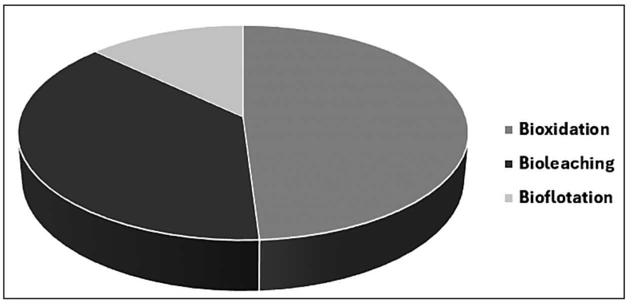

Figure 1 Application of *A. ferrooxidans* in PGMs processing as per the articles reviewed

cessing and in some articles done prior flotation (also referred to as biomodification). Whereas bioleaching was done to preconcentrate PGMs by leaching the metals from PGM-bearing base metal sulphides. *A. ferrooxidans* was further applied in flotation where selective flotation was desired. The application of *A. ferrooxidans* in biohydrometallurgy and bioflotation is further discussed below.

Biohydrometallurgy utilizes the inherent oxidation capabilities of natural bacteria to dissolve metal sulphides, enabling the extraction and retrieval of precious and base metals from primary ores and concentrates [4,5]. In the context of PGMs, particularly gold processing, Acidithiobacillus ferrooxidans has been effectively employed for biooxidation, which can be seen as a process of liberating gold prior to leaching [6-8]. Bacterial oxidation serves as an alternative to conventional methods like roasting or pressure oxidation, which often yield insufficient gold recovery through direct cyanidation. Through the biooxidation process, microorganisms like *A. ferrooxidans* are utilized to oxidize sulphide minerals, thereby freeing gold particles from the sulphide matrix and making them more accessible for subsequent cyanidation [8,9].

At present, there are four common pre-treatment techniques employed in mineral processing: oxidative roasting, pressure oxidation, chemical oxidation, and biological oxidation. Among these techniques, biooxidation pre-treatment has gained attention as a cost-effective and environmentally friendly method for extracting metals from various minerals, ores, and waste materials, while also minimizing environmental impacts. Over the past decade, there has been a significant surge in interest in bioleaching technology due to the heightened stringency of environmental protection regulations. Consequently, the application of bio-hydrometallurgy, which involves the use of bioleaching for metal extraction, has experienced considerable growth.

The oxidation mechanisms can occur through direct or indirect mechanism . Direct mechanism involves physical contact between the bacteria and the sulphide minerals, e.g. pyrite (FeS_2), pyrrhotite (FeS), arsenopyrite (FeAsS) and chalcopyrite ($CuFeS_2$), which then react with dissolved oxygen to convert sulphide-sulphur to sulfate or elemental sulphur [6,7].

Indirect mechanism involves oxidation-reduction cycle of ferrous and ferric ions in mineral-solution interface during biooxidation process according to the following reaction [6,7]. The ferric ion generated by reaction (5) further plays a role in subsequent oxidation of metal (II) sulphide (MS) into its divalent ions and elemental sulphur according to the following reaction [6].

The application of *A. ferrooxidans* in Bioflotation

The choice of ore beneficiation method for PGMs depends on the ore grade being processed. Previous beneficiation routes have been designed for high-grade PGM ores and are not economically viable for treating low-grade ores. Current research efforts are focused on improving the recovery of PGMs from low-grade UG2 ores and secondary sources. The metallurgical field is actively working towards optimizing the mineral beneficiation process in an economically and environmentally friendly manner, with the aim of minimizing the environmental impact of by-products and tailings [2-4]. Microorganisms offer a potential solution as their usage as reagents is recyclable, economically feasible, and environmentally friendly.

Initially, *A. ferrooxidans* was investigated in bioflotation studies as a safer alternative to cyanide for pyrite depression during coal desulphurization. The attachment of the bacterium to the pyrite surface led to significant chemical modifications, rendering the material hydrophilic. Subsequent investigations expanded to other base mineral sulphides, including chalcopyrite ($CuFeS_2$), galena (PbS), pyrrhotite ($Fe_{(1-x)}S$), and sphalerite (ZnS). It is worth noting that PGMs are typically associated with base metal sulphides, and their recovery during the concentration process (flotation) is directly tied to the recovery of these base metal sulphides [1]. This paper discusses the application of *A. ferrooxidans* in flotation, specifically in relation to base metal sulphides, which serve as carriers for PGMs.

Fe- sulphides

A. ferrooxidans is mainly applied in flotation where separation of pyrite from other base metal sulphides like chalcopyrite is desired. This is because of the (a) presence of aporusticyanin on the surface of the bacterial cell which causes *A. ferrooxidans* to preferentially adhere on pyrite over other sulphides, (b) the formation of hydrophilic jarosite on the surface of pyrite [2], (c) the development of oxidized layers on pyrite surface because of protracted bacterial interaction, and (d) the rise in bacterial attachment density on pyrite increases in *A. ferrooxidans* depressant capacity [2]. The presence of aporusticyanin on the bacterial cells is ranked as one of the reasons *A. ferrooxidans* can be used for pyrite depression replacing the use of sodium cyanide which is well known as one of the depressants of sulphides. The efficiency of *A. ferrooxidans* is known to be at a pH of less than 2, because that is the favourable condition for its growth. However, for efficient separation, *A. ferrooxidans* depress pyrite under mildly alkaline conditions (which favours xanthate-copper sulphides interaction) because the production of EPS is not dependent on pH [2] meaning the bacteria does not lose its depressing ability even in alkaline conditions. The separation of copper sulphides and pyrite occurs at a pH ranging from 10-12 when lime is used, which brings about an advantage the bacteria has over conventional pyrite depressants. *A. ferrooxidans* has similar impact on pyrrhotite [2], because of *A. ferrooxidans'* preference for pyrrhotite, the mineral become hydrophilic, and this induced hydrophilic nature enhances depression of pyrrhotite. The high density of the hydrophilic cells produced after microbial attachment mitigates the expected increase in floatability of pyrrhotite caused by the creation of S^0 [2].

Cu-Fe-sulphides

A. ferrooxidans has high affinity for iron sulphide minerals as iron (II) and oxidized sulphur is their main source of energy. In a case where sulphides are bearing copper, Acidithiobacillus family preferably adheres slowly onto Cu-sulphides because copper ions are considered toxic to this bacteria group [2]. The biomodification carried out by *A. ferrooxidans* culture combines the action of bacteria and ferric ions. In the case of Cu-sulphides biomodification (partial oxidation) is an indirect mechanism wherein the *A. ferrooxidans* do not adhere to the minerals surfaces meaning biomodification is imposed by Fe (III) ions produced after iron (II) oxidation. This form of Cu-sulphides oxidation is by means of polysulphides which is a combination of microbially induced H^+ and Fe (III) from the bacterium conditioning solution. Regardless of ever-existent controversies over the oxidation products of sulphide minerals, it is accepted that the formation of S^0, in moderately oxidizing potentials, is the most obvious mechanism for explaining the increase in hydrophobicity of sulphides.

From the article [2], it was discovered that *A. ferrooxidans* may be good secondary collectors of chalcopyrite, depending on the solution pH conditions (acidic or alkaline). In acidic conditions, it was noticed that pyrite and chalcopyrite were collected, however, in alkaline condition chalcopyrite is collected, while for pyrite *A. ferrooxidans* renders hydrophilic nature on the mineral, reducing its floatability.. According to the researcher [3], cells that had been pre-cultured on solid substrates like elemental sulphur were less effective at suppressing pyrite and chalcopyrite than cells that had been grown on a medium with soluble ferrous iron. Preconditioned bacterial cells made the cell surface more hydrophobic, making them fewer effective depressants for the tested mineral sulphides when grown on a solid substrate like elemental sulphur [2].

CONCLUSIONS

Metallurgical industry is moving towards greener mineral processing and beneficiation routes and biotechnology is the solution that is applied to hydrometallurgy (leaching and oxidation) and mineral processing (flotation). *A. ferrooxidans* is one of the microorganisms that continues to play a significant role in metallurgical industry due to its ability to interacts with PGMs-bearing sulphides minerals. To fully adapt the use of *A. ferrooxidans* there is a need to understand the theory around the mechanism of *A. ferrooxidans* interaction with base metal sulphides in bioleaching and *A. ferrooxidans* interaction with base metal sulphides in flotation, and *A. ferrooxidans* interaction with conventional reagents. The need to understand the interaction between *A. ferrooxidans* and the conventional reagents is to establish a model on the bacteria's capacity in leaching and flotation which will provide a standard conditioning step that maximizes the activity of the bacteria while increasing the concentrate recovered either in leaching or in flotation.

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Note: The responsible for English language is Nokubonga Given Zulu, Johannesburg.