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Application of Biohydrometallurgy to Copper Mining in Zambia: Prospects and Opportunities

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Abstract: The consumption of copper worldwide has grown fast since 2000; the mining industry is increasingly faced with the necessity to process low grade ores and waste tailings, from current mining operations. The economic extraction of copper from low-grade ores requires low-cost processing methods such as biohydrometallurgy. This study looks at a general panorama of copper mining in Zambia and discusses biohydrometallurgy as a novel and economically viable process for copper extraction. It also presents future prospects of this technology in Zambia. Since early 1930s, the copper mining industry has been the economic and social pillar of Zambia with about 80% contribution to the total export earnings and about 13% Gross Domestic Product (GDP). Mineralisation in the Zambian Copperbelt is dominantly sulphide, comprising of chalcopyrite, bornite and chalcocite among others with grades of the ore deposits generally in the range of 3 - 4% copper and 0.1 - 0.2% cobalt. Huge low grade copper deposits (~0.67% Cu) which are dominantly sulphides (chalcopyrite) were recently discovered in Lumwana area in the North-western Zambia and are currently being exploited. Reports show that more than one billion tons of ore (c. 2.7% Cu) has so far been mined from the mines on the Copperbelt Province of Zambia and conservative estimates suggest that a further two billion tons await exploitation. This provides considerable opportunities for further exploration and mining in Zambia. However, there is currently no commercial copper processing plants in operation on a large-scale in Zambia via biohydrometallurgical process. In order for Zambian mining industry record considerably higher recoveries at inherently lower capital cost, there is need to focus effort on research in this innovative technology and its application.

Keywords: Biohydrometallurgy, Bioleaching, Copper Mining, Mining in Zambia

1. Introduction

Historically, the mining industry has been the economic and social backbone of Zambia and contributes about 80% of the total export earnings and about 13% of the GDP [1]. One of world's largest sources of copper ore is found on the border of Zambia and the Democratic Republic of Congo (DRC), in a region known as the Copperbelt [2]. Since 1928 when the first commercial copper mine was commissioned at Roan Antelope (now Luanshya), a number of mineral deposits, besides copper, such as emeralds, cobalt, coal and zinc have been discovered as well as significant quantities of selenium and silver, together with minor gold and platinum group elements. Most of these minerals are also produced as important by-products of the copper mining and processing. This demonstrates considerable opportunities for further exploration and mining.

Copper demand in the future is projected to increase because of its application in new marine uses such as ship hulls and sheathing of offshore platforms, electric vehicles, earth-coupled heat pumps, solar energy, fire sprinkler systems and nuclear waste disposal canisters [3]. The increased use of copper due to its electrical conductivity, corrosion resistance, thermal conductivity and new applications has gradually led to a decrease in exploitable ore reserves [4]. In Zambia, copper mostly occurs in form of sulphide and oxide mineralization. The common ore minerals mined include; chalcopyrite, covellite, chalcocite, malachite and azurite that have insignificant practical value of their own. In view of this, long and complex chemical processes for mining. The copper mining industries in Zambia have been employing traditional techniques which involve crushing and grinding of copper-containing ore, followed by application of tremendous amount of heat or toxic chemicals [5]. These processes are appropriate on high-grade sites as they are energy-intensive, and therefore costly. The grade of copper ore has depreciated in the last decades, with many sites reporting deposits containing less than 1.0% copper grades [6]. Furthermore, the increase in mining activities in Zambia has been associated with highly disruptive effects such as geotechnical issues, land degradation, air, soil and water pollution which pose long term threats on the local livelihood of the people and the environment and biodiversity [7].

The last decade has particularly observed change in the copper prices which has seriously influenced the global mining companies. There has been dramatic increase in the prices to unprecedented high levels followed by an unparalleled event of declining copper prices [8]. This has resulted in rapid increase in production costs leading to mines targeting higher copper grades and cutting off of the work force. Figure 1 below shows copper output and price movements in Zambia covering the period of 1930 – 2010. The future development with regards to low-grade copper ores and waste tailings, from current mining operations has motivated this research to focus more on novel and economically viable new technologies for metal extraction. Copper extraction by microbial process 'Biohydrometallurgy' also known as bioleaching has emerged as an alternative technology.

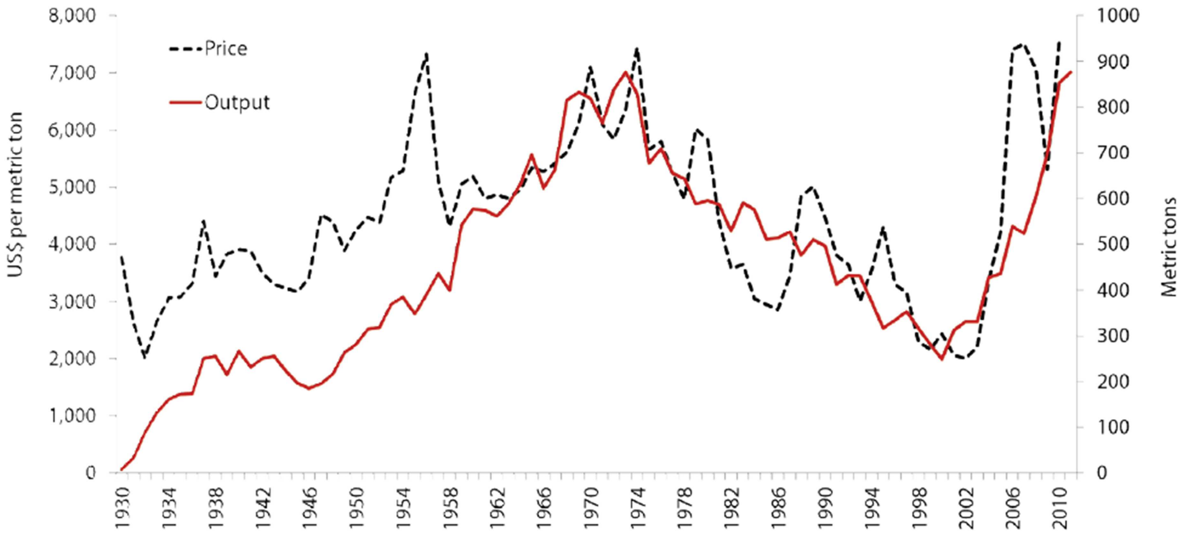

Figure 1. *Copper output and price movements in Zambia's mining history [9].*

Biohydrometallurgy is essentially the application of biotechnology to processing minerals [8, 10]. Technically, the process is a branch of hydrometallurgy, but it involves the use of microorganisms to biooxidise sulphide minerals ore from low-grade copper ore deposits [11]. The bacterial metabolic processes lead to the metal extraction via bio-oxidation process. For example, *Acidothiobacillus ferroxidans* is a famous lithoautotroph which use ferrous iron (Fe^{2+}) as electron donor along with elemental sulphur and their activities have been reported to be associated with mineral ore processing [12]. The report conducted by [3] shows that the technique of bioleaching of secondary copper ores and mixed sulphide/oxide ores is so effective that it's now estimated to represent 20 - 25% of the world's copper production. Furthermore, the process has lower capital and operating costs than competitive technologies and therefore economical to implement during mining down-cycles compared to other processes. A comparative analysis was carried out by [13] to observe how copper and gold biohydrometallurgical operations took the role with the increase and decline of metal prices over time. The results indicated that most biohydrometallurgical innovations have been commercially implemented during times of low metal prices, which could be interpreted to mean the mining industry is more inclined to apply this process during leaner times. Although biohydrometallurgy has been globally applied to the recovery of copper and is piloted and commercialized in many countries worldwide with many empirical studies carried out, the technology in Africa is in its infancy stage with notable mining plants utilizing this technology such as gold plant at Fairview in South Africa, Bogosa and Ashanti's Sansa plant in Ghana and cobalt plant at Kasese in Uganda [14, 15].

In spite of Zambia being one of the major copper producing countries in the world, there has been hardly any extensive research on bioleaching conducted in the country with regard to an assessment of its practicality. Currently, there is no commercial copper processing plants in operation on a large-scale via this innovative technology. This study looks at a general panorama of copper mining in Zambia and discusses biohydrometallurgy as a novel and economically viable process for copper extraction. It also presents the future prospects of this technology in Zambia.

2. Copper Extraction Via Conventional Methods

The conventional methods of copper extraction can be classified as either hydro-metallurgical or pyro-metallurgical [3, 16]. After mining, the ore is crushed and milled into a fine pulp, which is then concentrated by flotation using chemical reagents. The ore concentrate is leached followed by the use of various techniques to concentrate the metal using ion exchange or solvent extraction (SX) and electro-winning (EW) to deliver a high-grade copper cathode. The other method of copper extraction is the pyro-metallurgical process. In this process the concentrate from flotation is smelted and electrolytically refined. Copper cathodes of 99.9% purity may be shipped as melting stock to mills or foundries [16]. Cathodes may also be cast into wire rod, billets, cakes or ingots, generally, as pure copper or alloyed with other metals [3]. Figure 2 shows general processes involved in hydro and pyro-metallurgical processes.

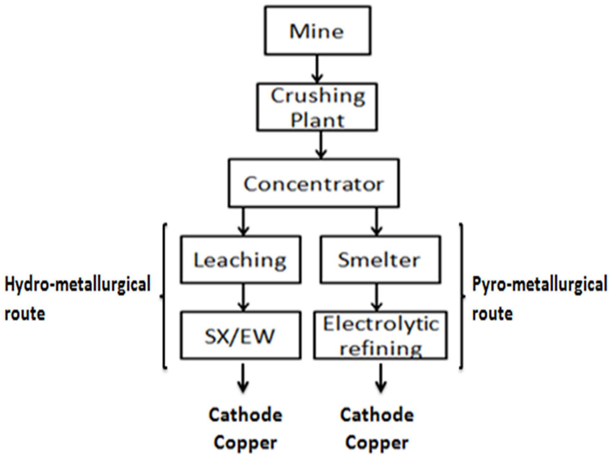

Figure 2. *Copper extraction via conventional methods.*

3. Geology and Mineralisation of the Zambian Copperbelt

The Zambian Copperbelt is part of the Central African Copperbelt which forms one of the world's largest metallogenic provinces containing approximately 40% of the world's cobalt mineral reserves and 10% of the world's copper reserves [2]. Copper-cobalt deposits in the Central Copperbelt are hosted within the strongly deformed geological structure called the Lufilian arc that extends from North-eastern Angola through southern Democratic Republic of Congo and into Zambia. Mineralisation in the Zambian Copperbelt is dominantly sulphide, consisting of chalcopyrite, bornite and chalcocite variably accompanied by pyrite, pyrrhotite, carollite, covellite and diginite [17, 18]. It is further reported that the grades of the Zambian ore deposits are commonly in the range of 3 - 4% copper and 0.1 - 0.2% cobalt [11]. Huge low grade copper deposits (~0.67% Cu) which are dominantly sulphides (chalcopyrite) were discovered in Lumwana area in the North-western Zambia [6] and are currently being exploited by Barrick Gold Corporation.

4. Historical Background of Bioleaching

Historical records indicate that bioleaching of low-grade metals on a large-scale has been in existence since early 1960s, though prior to that the process had been empirically exploited without realization of the microbes playing the major role in the extraction process. In 1964 in Wyoming, USA, reference [19] reported on the bioleaching of low-grade uranium. The research on bioleaching technology was not very active mainly due to insufficient information on the microbe's morphology and their ability to extract metals from their ores. During the same period, some demonstrations, in Bingham Canyon, Utah and the Chino mine in Mexico, were done on the presence of *T. ferroxidans* in acid mine drainage (AMD) and its role in leaching copper form minerals such as chalcopyrite, chalcocite, chalcocite, bornite and covellite [21]. Following that, research and development activities in bioleaching flourished rapidly and by 1980s, a first bioleaching plant in Africa was commissioned at the Fairview Gold Mine near Barberton in South Africa. Bioleaching has recently become a competitive and preferred technology to conventional pyro/hydro-metallurgical processes [5].

5. Bioleaching Technology

5.1. General Description of Biohydrometallurgy

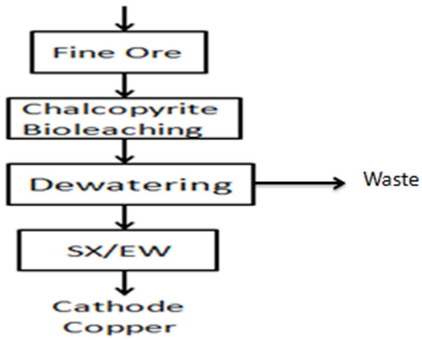

Figure 3. *Simplified flowsheet of an integrated circuit for the bioleaching of chalcopyrite concentrate.*

Bioleaching involves the dissolution of metals from their mineral sources by certain naturally occurring microorganisms [21]. It is the utilization of microorganisms through a process of biooxidation of ferrous iron to ferric iron, the main oxidant that chemically dissolves the metal ore. In the case of copper extraction, copper is liberated from its copper surphide bearing ores such as chalcopyrite, covellite, and chalcocite using micro-organisms [22, 23]. The efficiency of bioleaching process is a function of the operating time. The residence time is critical for bacterial adaptation to their environment. The dissolution of sulphide minerals by microorganisms mainly involves direct and indirect leaching mechanisms [21]. In direct leaching, the bacteria attach themselves to the metal sulphide crystals within the rock and through oxidation; the metal is dissolved by converting the metal sulphide crystals into soluble sulphates. Indirect leaching involves re-oxidation of the ferrous iron back to ferric form and oxidation of the elemental sulphur formed in some cases [22]. The processes are achieved with the help of microorganisms. The sulphide mineral is then oxidized chemically by ferric irons thereby producing ferrous iron. Indirect leaching does not involve bacterial attachment to the mineral surface [5]. Figure 3 shows a simplified flowsheet for the commercial bioleaching of chalcopyrite.

5.2. Type of Bioleaching Techniques

There are various types of techniques that exist within the bioleaching. Currently, the two (2) prominent methods are Tank and Heap bioleaching. Tank bioleaching involves large aerated tanks to facilitate continuous flow mode of operation [24, 25]. The selection of microorganisms is in such a way that dissolution of minerals is enhanced as well as creating favorable conditions for rapid conversion of sulphide minerals. This process is not energy intensive as sterilization is not necessary because they operate under acidic environment [26]. Tank bioleaching is usually used for high valuable materials such as gold owing to high capital cost required. Heap bioleaching involves stacking crushed ore on plastic mats and spraying a solution with liquor solution containing microorganisms with rich microbial nutrients. The solution drains through the heap material and collected and re-sprayed over until its mineral content is rich enough. The solution is then drained off and the desired metal is extracted by conventional means such as electrowining [27]. The kinetics of microbial ferrous iron oxidation is faster in tank leaching in comparison to heap bioleaching [15, 26]. It is for this reason that huge research undertakings have been carried out to improve the kinetics of the bioleaching process.

5.3. Microorganisms Involved and General Mechanism of Bioleaching

Most of the microorganisms responsible for bioleaching are autotrophic, and are capable of synthesizing their own food from inorganic substances using light or chemical energy. These microbes usually get the required nutrients from iron and/or sulphur containing mineral suspension in solution [28]. They are also referred to as acidophilic in nature as they can only survive and thrive in an acidic environment. The process of biooxidation provides them with a source of energy that comes from the loss of electrons from an atom [15]. The bacteria used in bioleaching process mostly have a wide range of operating temperature. The *mesophiles* operate between 30 and 42°C; include several species of *Acidithiobacillus* and *Leptospirillum.* Moderate *thermophiles* exist within temperature range of 45 to 55°C, such as *Sulfobacillus* and *Ferroplasma* species. The extreme thermophiles thrive between 60 and 90°C and are mostly archaea which include various species of *Sulfolobus* and *Metallosphaera* [26].

Reference [29] proposed a model with two different mechanisms (direct and indirect mechanisms) for the bioleaching of metals from their mineral ore. Under direct leaching, the microbe membrane interacts directly with the sulphide surface via enzymatic mechanisms. This mechanism is observed if the cells attach to the mineral surface and this process takes place within minutes or hours. Indirect mechanism involves oxidation of reduced metal which is mediated by ferric ions (Fe^{3+}) formed from the microbial oxidation of ferrous ions (Fe^{2+}) compounds present the mineral [21]. Ferric ion is able to oxidize metal sulphides and is reduced chemically to ferrous ions. Ferrous ions can be oxidized microbially to ferric ions again. In this case, iron has a role as electron carrier. The study conducted by [31] further proposed that no physical contact is required in order for iron to be oxidised. The equation below describes the direct and indirect mechanism for the oxidation of metal sulphides.

Direct mechanism:

In this process, metal sulphides can be oxidised directly by T. ferroxidans to soluble metal sulphates as shown in equation 1.

$$MS + 2O_2 \xrightarrow{T.ferroxidans} M^{2+} + SO_4^{2-} \quad (1)$$

Theoretically, the mechanism can be continued until all the substrate (MS) is converted to product (MSO_4). This can be represented as follows:

Chalcopyrite: $4CuFeS_2 + 17O_2 + 2H_2SO_4 \rightarrow 4CuSO_4 + 2Fe_2(SO_4)_3 + 2H_2O$

Pyrite: $4FeS_2 + 15O_2 + 2H_2O \rightarrow 2Fe_2(SO_4)_3 + 2H_3SO_4$

Chalcocite: $2Cu_2S + 5O_2 + 2H_2SO_4 \rightarrow 4CuSO_4 + 2H_2O$

Covellite: $CuS + 2O_2 \rightarrow CuSO_4$

Indirect mechanism:

This mechanism is represented by the oxidation of sulphide minerals by ferric ions as shown in equation 2. The reaction is occurs under the action of *Thiobacillus*, whereas the chemical reaction in equation 3 takes place without any association of bacteria. The oxidation of elemental sulphur as shown in equation 4 also occurs by *Thiobacillus.*

$$4FeSO_4 + 2H_2SO_4 + O_2 \xrightarrow{Thiobacillus} 2Fe_2(SO_4)_3 + 2H_2O \quad (2)$$

$$MS + Fe_2(SO_4) \rightarrow MSO_4 + S^o \quad (3)$$

$$2S^o + 3O_2 + 2H_2O \xrightarrow{Thiobacillus} 4H^+ + 2SO_4^{2-} \quad (4)$$

Metal desolution takes place by a cyclic process between reactions shown in equation 2 and 3 and the generation of H^+

during sulphide oxidation in equation 4 enhances the overall efficiency. The following equations represent chemical oxidation processes;

Chalcopyrite: $CuFeS_2 + 2Fe_2(SO_4)_3 \rightarrow CuSO_4 + 5FeSO_4 + 2S^o$

Pyrite: $FeS_2 + Fe_2(SO_4)_3 \rightarrow 3FeSO_4 + 2S^o$

Chalcocite: $Cu_2S + 2Fe_2(SO_4)_3 \rightarrow 4CuSO_4 + 4FeSO_4 + 2S^o$

Covellite: $CuS + Fe_2(SO_4)_3 \rightarrow CuSO_4 + 2FeSO_4 + S^o$

The mechanism of bioleaching is shown below in figure 4 according to [29].

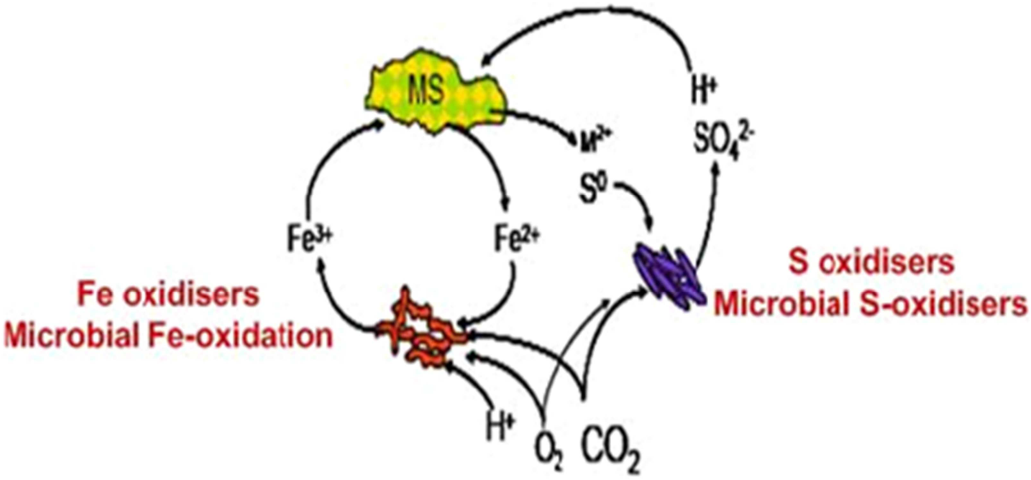

Figure 4. *Schematic representation of the mechanism of bioleaching [31].*

6. Factors Affecting Bioleaching

Although bioleaching has been studied more than 50 years, there are a number of outstanding issues that remain. For example, the bioleaching process is still slower than conventional methods, which may increase the cost of production. Furthermore, the ability to control microbial growth is a key success factor which is influenced by many variables: types of microorganisms, ore types, type and quantity of metal, nutrient addition, oxygen supply, pH, temperature, pulp density and agitator shear rate. The yield of metal being extracted, via bioleaching process, is highly dependent on these factors [5, 31]. For the process to be competitive, there is need to optimize the operating parameters which include; pH, temperature, humidity, nutrients, energy source, particle size and excess of oxygen. These working conditions are essential for bacterial growth to favour metal extraction, acid consumption reduction and rate of metal recovery [28]. The study carried out by [32] showed that bioleaching using pure cultures and mixed cultures, and then compared their efficiency in terms of metal dissolution. The study further revealed that oxidation of ore by mixed cultures of bacteria takes place at a higher rate than by using pure cultures. However, it is very complex to explain how consortia of bacteria appear to work, compared to pure culture. The bioleaching of a given ore from different sources and/or different types of ores also requires test studies to be conducted, despite the success of metal extraction by the same bacteria in other ores. Consequently, it is necessary to find an optimum condition for a particular case.

7. Future Prospects

According to [33], more than one billion tons of ore (*c.* 2.7% Cu) has so far been mined from the mines on the Copperbelt Province of Zambia and conservative estimates suggest that a further two billion tons await exploitation. Due to the long term history of mining on the Zambian Copperbelt, the potential exists for the major additional source of copper in the form of old tailings plants. Reference [2] also reported that about 1 – 2% of copper has been lost from the tailings dams due to the relatively inefficiency of metallurgical extraction processes. Re-treatment of old tailings is therefore high potential source of copper and cobalt recovery for current and future investments.

The future of biohydrometallurgcal technology application, on a large scale, in Zambia is a practical option because the low and slow recoveries are countered by the low processing costs. Not surprisingly, the bioleaching of chalcopyrite, both the most abundant and the most refractory copper sulphide, is a key mining industry target. However, most of the technological developments have taken place with the bioleaching of chalcocite and other less refractory sulphide minerals [8]. The most likely prospect for the implementation of biohydrometallurgy at existing operations in Zambia is where there is an existing acid leach operation with associated SX-EW infrastructure i.e. Nchanga and Mopani mine in the Copperbelt province and Kansanshi mine in North-western province. The advances that have been made in recent years in optimizing the design, operation and control of biohydrometallurgical operations mean that considerably higher metal recoveries can now be attained at significantly reduced leach cycle times. In this regard, the inherently lower capital cost may make this technology favorable to compete with flotation and concentrate production for the treatment of secondary sulphide resources.

Progressive works from this study will focus on investigating the amenability of copper sulphide minerals, from various mines in Zambia to bioleaching. This preliminary leaching kinetics data may be useful for the design, and possible development and operation, of tank or heap bioleaching operations.

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Biography

Ronald Ngulube is currently working as Lecturer/Consultant at the Copperbelt University, Zambia. He is a holder of MSc in Environmental Biotechnology at the University of Westminster, United Kingdom and BEng in Chemical Engineering from Copperbelt University, Zambia. Mr. Ngulube has over six years of industrial experience in hydrometallurgy and worked as Assistant Plant Manager, Senior Process Engineer, and Project Metallurgist among others at Konkola Copper Mines Plc, Zambia. His main research interest is in; treatment of copper sulphide ores by bioleaching technique, bioremediation of mine effluent by sulfate reducing bacteria and application of genetic engineering in biofuels production.