The present work was submitted to the Faculty of Engineering

Leaching of the copper mineral-bearing ore

Bachelor Thesis

by

Dulguun Munkhochir (15033825435704)

Supervisor 1 / Examiner 1	**Prof.Bayanmunkh Myagmarsuren**
Supervisor 2 / Examiner 2	**Dr.Ariuntuya Tserendorj**

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Statutory Declaration

Munkh-Ochir Dulguun	ID 15033825435704
Last Name, First Name	Student ID Number

I hereby affirm in lieu of an oath that I provided the submitted bachelor thesis

Leaching of the copper mineral-bearing ore

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Abstract

Hydrometallurgy has become a key process in the production of copper, accounting for more than 30% of global copper production. In the leaching process of oxidized copper ore, dilute sulfuric acid has traditionally been used as the leaching agent. The use of sulfuric acid has certain drawbacks, including environmental concerns and the requirement for high energy input during processing. Therefore, researchers have been investigating alternative leaching agents to improve the efficiency of the process while minimizing its impact on the environment.

One such alternative is alkaline glycine, which has shown good results as a lixiviant for copper-bearing mineral ores. The aim of this bachelor thesis was to investigate the leaching behavior of copper-bearing mineral ores using glycine and sulfuric acid solutions. The primary objective was to develop an environmentally-friendly process for treating low-grade copper ores that fall below the cut-off grades for conventional processes.

This study's results revealed that using glycine as a lixiviant in the agitation tank leaching process resulted in higher metal recovery rates compared to the conventional sulfuric acid reagent. Furthermore, increasing the concentration of the leach solution led to higher metal recovery rates over time. The dissolution of impurities in the glycine and sulfuric acid solutions was also found to be significantly lower than in conventional processes. This finding suggests that the use of glycine as a lixiviant in the leaching of low-grade copper ores can be a viable and more cost-effective alternative to traditional processes.

The findings of this study provide valuable insights into the potential of glycine as a leaching agent for low-grade copper ores. In order to achieve a more sustainable and environmentally-friendly approach to copper production. Overall, this research contributes to the ongoing efforts to develop more efficient and sustainable processes for the extraction of copper from mineral ores.

Acknowledgments

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1.Introduction

1.1 Background of this study

Copper ores are a valuable source of copper, but their extraction presents significant challenges due to the complex mineralogy and low copper grades. Traditional leaching agents, such as sulfuric acid, are not efficient for extracting copper from these ores, and often require high energy and water consumption. Alternative leaching agents have emerged as a potential solution to these challenges.

This study aims to evaluate the effectiveness of various alternative leaching agents for copper ores, including organic acids, ammonia, and unconventional leaching agents. The efficiency, kinetics, and selectivity of copper extraction will be assessed for each agent, and compared to traditional leaching agents.

The findings of this study may have significant implications for the development of sustainable copper extraction processes. By identifying more efficient and eco-friendly leaching agents, the environmental impact of copper mining can be reduced, while also increasing the efficiency of copper extraction. Additionally, the insights gained from this study may pave the way for the development of environmentally friendly processes for the extraction of other metals.

This study will evaluate the effectiveness of various alternative leaching agents for copper ore and their potential application in sustainable copper extraction processes. The findings may contribute to the development of more efficient and eco-friendly methods for copper extraction, while also providing insights for the extraction of other metals.

The extraction of copper from low-grade sulfide ores is a resource-intensive process that poses significant environmental challenges. In order to reduce environmental impact, alternative leaching agents have emerged as a promising solution. Among these agents, the leaching of oxidized ores with alternative agents is a promising but underexplored approach.

The purpose of this study is to evaluate the effectiveness of various alternative leaching agents for copper ores and compare performance with traditional leaching agents such as sulfuric acid. The alternative agents being examined in this study include organic acids, and unconventional leaching agents. The efficiency, kinetics, and selectivity of copper extraction will be assessed for each agent.

The results of this study could have important implications for the development of sustainable copper extraction processes that minimize environmental impact and reduce energy and water usage. The findings may also provide valuable insights for the mining industry to optimize copper extraction processes and improve efficiency. Additionally, exploring alternative leaching agents could lead to the development of environmentally friendly processes for the extraction of other metals.

1.2 Objectives of the study

The main aim of this bachelor thesis work is to achieve the following objectives:

- To explore and establish the leaching characteristics of copper ore minerals using alternative agents through agitation tank leaching.
- To examine the influence of process variables and impurities on the dissolution of copper from copper ore in the presence of sulfuric acid and glycine solutions.
- To investigate the impact of glycine leach solution concentration and leach solution flow rate on agitation tank leaching experiments.

The main significant outcomes would be:

- To address the challenge of treating copper ore in an environmentally friendly manner, an innovative process is being introduced.
- In order to determine the most effective reagent for the dissolution of copper ore and to compare its performance against the traditional method, a study has been designed to evaluate the use of glycine in comparison with sulfuric acid.

1.3 Hypothesis

The bachelor thesis work consists of two main experiments and analyzing results.

1. The leaching behavior of copper ore using sulfuric acid experiment carried out in a laboratory using leaching agitation tank equipment. It consists of main two tests including effect of initial concentration of sulfuric acid solution test which is expected outcomes are such as follows:

- As time progresses, a higher concentration of sulfuric acid leach solution would result in a corresponding increase in metal recovery.
- The sulfuric acid leach solution is expected to dissolve a minimal amount of impurities.

2. Also, the leaching behavior of copper ore using glycine will be carried out in laboratory and leaching in agitation tanks consisting of 3 main tests. The projected results are as follows:

- Testing suitable particle size using rod mill
- It is expected that the glycine-based leaching test will yield a higher metal recovery rate than the sulfuric acid-based leaching test.

2. State of the art

2.1 Chapter objectives

The primary objective of the thesis work is to propose and investigate how various leaching agents impact in the solution and metal recovery over time and study a new lixiviant for oxidized copper ores and comparison with typical leaching agents and its potential impact on the environment. The present chapter provides a comprehensive review of the existing literature pertaining to various aspects related to the integrated bachelor thesis work.

In a leaching process operation, selecting a lixiviant suitable for the specific ore is a critical step that requires careful consideration of the ore's chemical and physical properties. Factors such as mineralogy, particle size, and porosity can impact the efficiency of the leaching process and influence the selection of the appropriate lixiviant. The chemical composition of the ore is also an important consideration, as impurities may interfere with the leaching process or require a different lixiviant.

The choice of a suitable leaching agent for a given ore is a critical step in the process of metal extraction, and the properties and characteristics of the lixiviant are key considerations in this regard. A good lixiviant should have the ability to selectively dissolve the desired metal(s) while leaving other components of the ore intact. This selectivity can be influenced by various factors such as pH, temperature, and the presence of other minerals or impurities.

The lixiviant should be able to penetrate the ore particles effectively to ensure that the target metal(s) are exposed for dissolution. Maintaining a stable chemical environment throughout the leaching process is another critical aspect of a good lixiviant. This can be achieved through the use of appropriate buffering agents and by maintaining the appropriate pH range for the specific ore being treated. a good lixiviant should have a high solubility for the target metal(s) and a low solubility for other impurities. This can help to increase the efficiency of the leaching process by minimizing the loss of valuable metals and reducing the amount of impurities that need to be removed later on. Safety and environmental considerations may include factors such as toxicity, flammability, and biodegradability.

2.2 Copper resource and mineralogy

Copper mineralization occurs in various geological settings, with the three primary deposit types being porphyry-type deposits, strata-bound deposits, and massive sulfide deposits. Porphyry copper deposits are a significant global resource and currently serve as the primary source of copper mining to meet the ever-increasing demand. Porphyry copper deposits are a type of copper ore body that form through the action of hydrothermal fluids that originate from a large magma chamber situated several kilometers below the deposit. The name of this deposit type comes from the vertical dikes of porphyritic intrusive rocks that are present, either preceding or accompanying the fluids. As the deposit evolves, meteoric fluids may also come into contact with the magmatic fluids. Over time, numerous layers of hydrothermal alteration can envelop a central core of disseminated ore minerals that occupy hairline fractures and veins, creating a stockwork formation. Apart from copper, these deposits also hold considerable reserves of gold and molybdenum, with the latter being predominantly sourced from porphyry deposits.

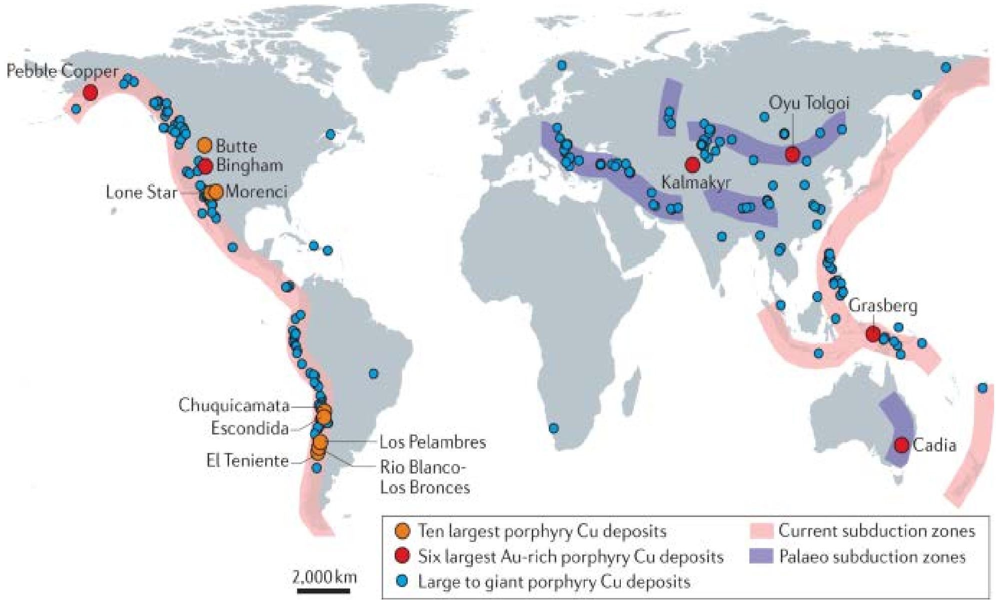


Figure 1 /Crustal magmatic controls on the formation of porphyry copper deposits/

Porphyry deposits are a crucial contributor to meeting the global demand for copper, as they constitute a significant source of metal extraction, accounting for roughly 60% of the world's copper supply. These deposits offer considerable potential as one of the largest and most widespread sources of copper. In Mongolia, copper deposits are widely distributed throughout the northern and southern regions of the country. Notable examples of porphyry copper deposits in Mongolia include Erdenetiin Ovoo, Saran-Uul, Tsagaan suvarga, and Oyu Tolgoi.

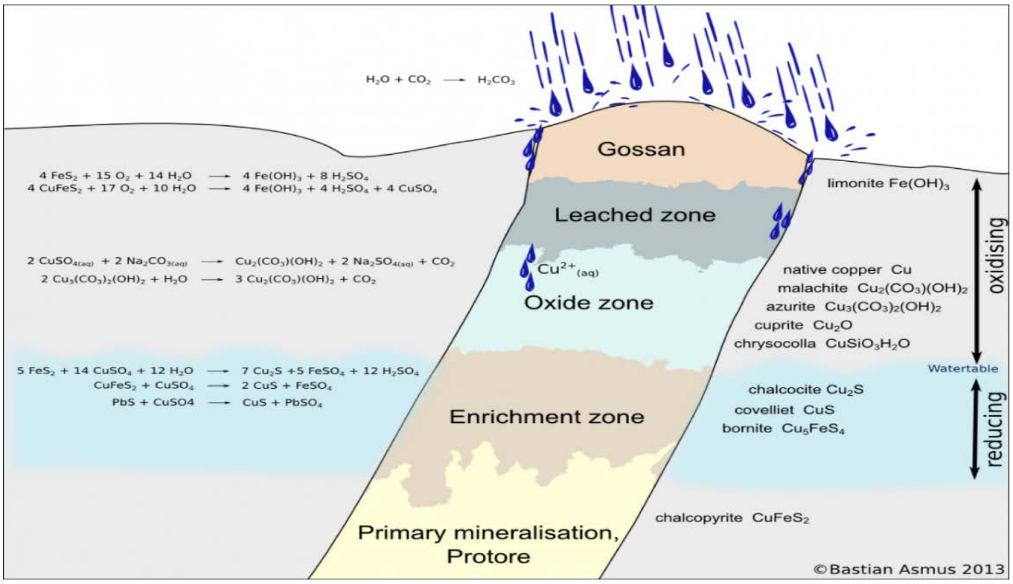


Figure 2 /Schematic view of a sulfide vein/

Mineralogical Copper Species	Associated Mineralized Zones	Concentration (wt%)	Grade (% Cu)
Chalcopyrite	Primary and secondary zones	0.0-1.5	0.5-1.5
Bornite	Secondary zone	0.5-2.0	1.0-3.0
Covellite	Supergene zone	25-50	66-68
Chalcocite	Supergene zone	60-80	79-80
Digenite	Supergene zone	30-60	65-70
Enargite	Advanced argillic zone	10-20	40-50
Tennantite-Tetrahedrite	Propylitic alteration zone	0.2-2.0	0.5-2.
Molybdenite	Potassic alteration zone	0.02-0.3	n/a

Table 1 /Main Mineralogical Copper Species and Associated Mineralized Zones in Porphyry Copper Deposits/

2.3 Copper processing

The ultimate aim of metal production is to achieve the maximum yield of pure metal with minimal impurities. To achieve this objective, mineral processing constitutes a crucial component in the production process. The mineral processing involves three main unit operations, including size reduction, size separation, and concentration. Comminution, which involves crushing and grinding, is a vital aspect of size reduction. Size separation and concentration processes are executed based on the physicochemical properties of minerals.

The mining industry commonly employs froth flotation as a concentration process, as noted by Wang et al. (2020). This technique is used for sulfide ores and is considered to be the most economical approach for producing a flotation concentrate for metal recovery via smelting. The Erdenet Mining Corporation and Oyu Tolgoi both use froth flotation to separate minerals based on their hydrophilic and hydrophobic properties. The effectiveness of this method in extracting valuable minerals while minimizing impurities has been well-established. Ultimately, the goal of metal production is to obtain high-quality metal with minimal impurities, and froth flotation plays a crucial role in achieving this objective.

2.3.1 Copper processing by hydrometallurgy

Hydrometallurgy is an established process that employs aqueous solutions for the recovery of copper and has been in use for several years. It is especially useful for the recovery of copper from ores with low-grade or complex mineralization that were previously not economically viable for conventional smelting methods. The need for alternative methods of copper extraction was necessitated by the existence of large ore bodies with low copper content that were difficult to process using existing techniques, prior to the development of froth flotation technology (Queneau & Osborn, 2019).

Hydrometallurgy provides a complementary approach to concentrator technologies for scavenging copper from tailings, as copper oxides are not readily floated using froth flotation. The copper recovery process involves leaching copper from the ore into an aqueous solution, typically sulfuric acid, followed by extraction using solvent extraction. The recovered copper is then subjected to electrowinning, a process where copper is electroplated onto a cathode, yielding highly pure copper metal that is suitable for further processing (Queneau & Osborn, 2019).

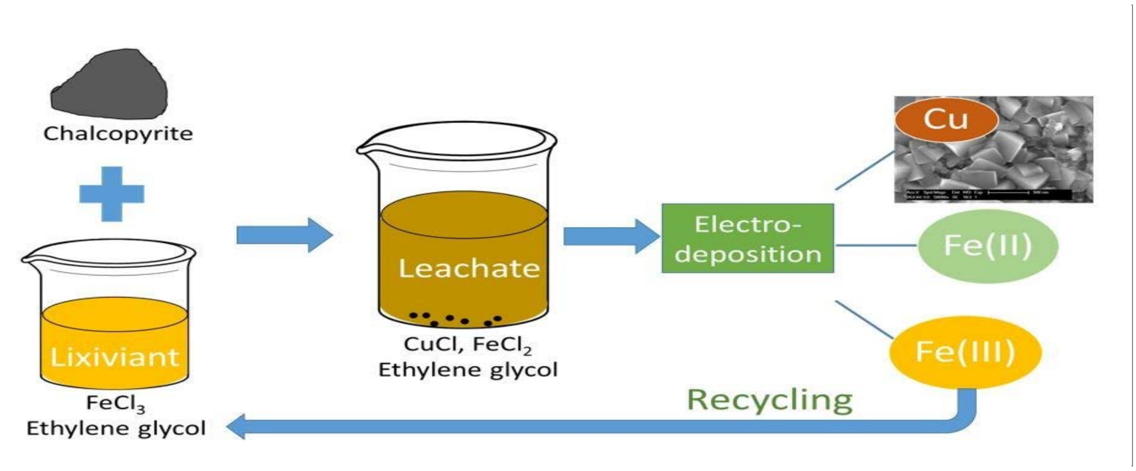


Figure 3 /Solve Metallurgical process of copper extraction using Ethylene glycol-FeCl3 as lixiviant/

In recent years, hydrometallurgical copper recovery methods have been developed to process concentrates of more complex ores, with the objective of eliminating the sulfur dioxide discharge problems associated with conventional smelting. Some of these newly developed methods use chemistry that yields elemental sulfur directly from the sulfur minerals present in the ores, resulting in a cleaner process overall. While all hydrometallurgical methods have a low air pollution potential, these newer methods offer an additional advantage (Queneau & Osborn, 2019).

2.3.2 Copper extraction by pyrometallurgy

Pyrometallurgical extraction of copper involves the utilization of elevated temperatures to liberate copper from sulfide ores. The particular techniques implemented in the process can diverge considerably based on multiple factors, including the source materials, process parameters, and the physical geometry of the vessel. Operations at the plant level may be conducted in a batch-wise, semi-continuous, or fully continuous mode, with the final product obtained being either blister copper or other refined forms of copper (Davenport, Bickert, & King, 2002).

The typical course of action entails the roasting of copper ore to eliminate sulfur, followed by the smelting of the remaining copper oxide with coke in a blast furnace to yield copper in a metallic form. However, this method can entail adverse environmental effects due to the release of sulfur dioxide gas, which can lead to acid rain and other types of atmospheric pollution. To alleviate these environmental repercussions, modern pyrometallurgy facilities for copper are often equipped with gas scrubbers and electrostatic precipitators to capture sulfur dioxide emissions and diminish their environmental footprint and efforts are exerted to optimize the processing parameters and heighten the efficiency of the process (Davenport et al., 2002).Although copper pyrometallurgy has been extensively applied for centuries and continues to be used across various regions worldwide, there remains a necessity to enhance the method further and curtail its environmental impact.

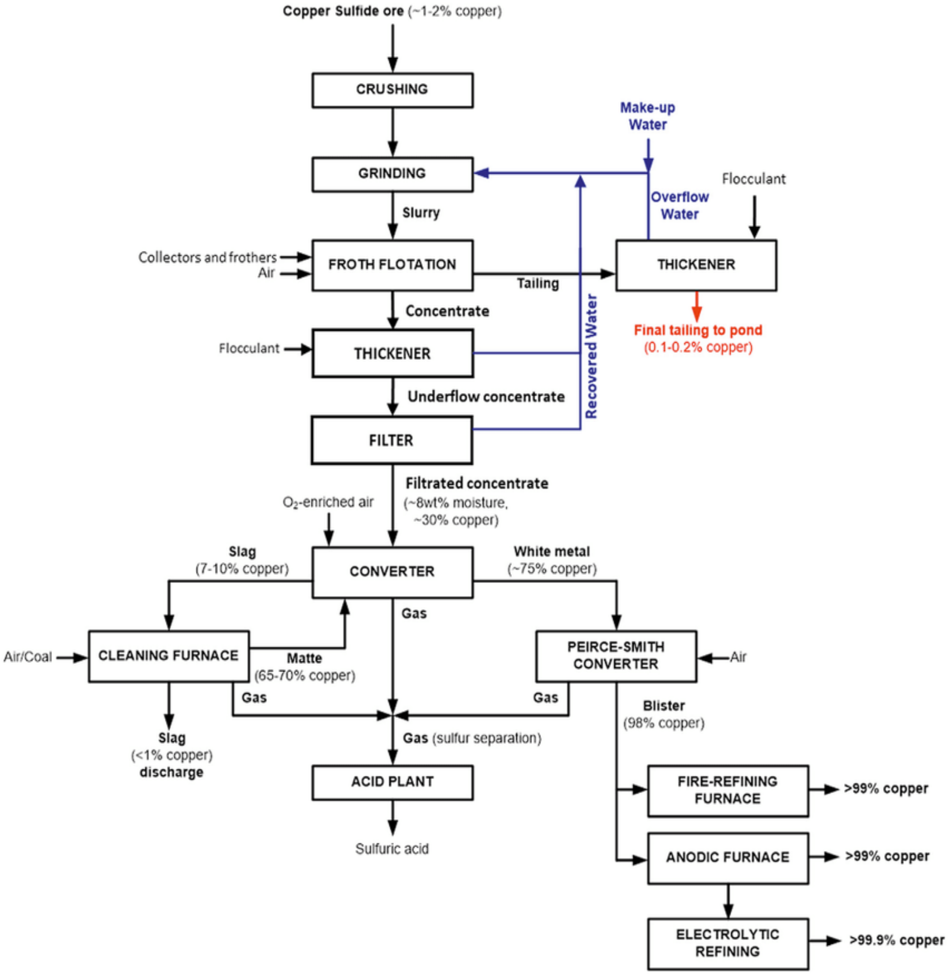


Figure 4 /Simplified flow-sheet of pyrometallurgical process for copper extraction/

2.4 Copper leaching

Leaching is a complex hydrometallurgical technique whereby metal ions are extracted from mineral ores via the dissolution of metal-bearing minerals using a suitable solvent, followed by the separation of the resulting solution from the insoluble portion, and ultimately the recovery of the metal ions through a range of techniques.

The importance of thermodynamic aspects in leaching conditions cannot be overstated, as they enable the evaluation of the dissolution process using a comprehensive understanding of the underlying thermodynamic principles, which can be obtained from the Pourbaix diagrams. Kinetic considerations play a crucial role in selecting the appropriate combination of reagents and their concentrations in hydrometallurgy, as the attainment of satisfactory free energy changes associated with the proposed reaction is a key determinant of successful extraction, and the optimization of the reaction kinetics is paramount in ensuring efficient and cost-effective metal recovery.

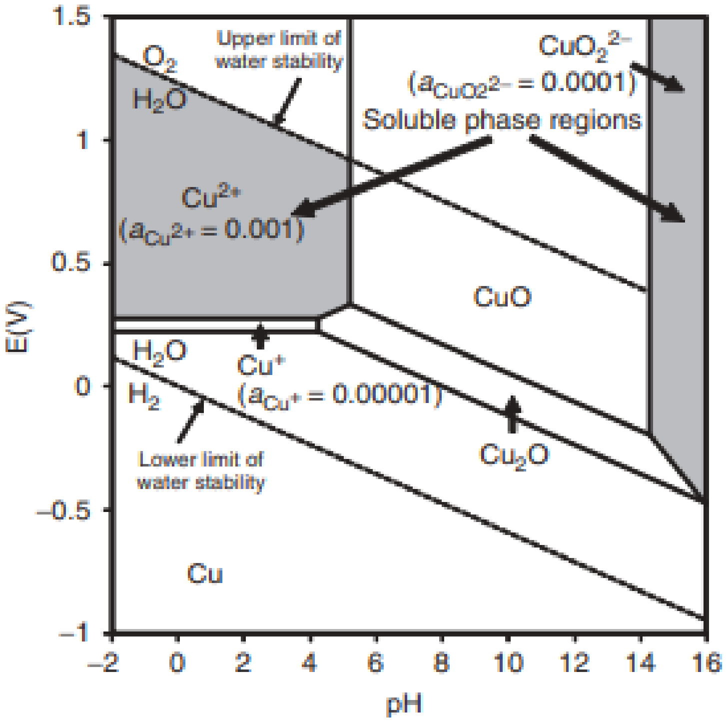


Figure 5 /Simplified copper phase diagram showing phase stability regions.

All copper species are shown in figure 5, leaching occurs in shaded regions where soluble species are stable the pH and electrode potential (in volts) of the solution are depicted on the horizontal and vertical axes, respectively, in the Pourbaix diagram of copper. Distinct regions on the diagram correspond to various phases or species of copper that are stable under varying conditions of pH and potential. Copper metal remains thermodynamically stable in the area below the Cu2O line, whereas Cu2O is the stable phase above this boundary. Similarly, CuO is the stable phase above its corresponding line.

Copper Oxide Mineral	Chemical Formula	Leaching Chemical Formula
Copper	Cu	Cu + H2SO4 → CuSO4 + H2
Cuprite	Cu2O	Cu2O + H2SO4 → CuSO4 + H2O
Tenorite	CuO	CuO + H2SO4 → CuSO4 + H2O
Azurite	Cu3(CO3)2(OH)2	Cu3(CO3)2(OH)2 + 2H2SO4 → 3CuSO4 + 2CO2 + 5H2O
Malachite	Cu2CO3(OH)2	Cu2CO3(OH)2 + H2SO4 → CuSO4 + CO2 + 2H2O
Chrysocolla	Cu2-xAlx(H2-xSi2O5)(OH)4	Cu2-xAlx(H2-xSi2O5)(OH)4 + 2H2SO4 → (Cu,Al)SO4 + 2SiO2 + 6H2O
Atacamite	Cu2Cl(OH)3	Cu2Cl(OH)3 + 3H2SO4 → 2CuSO4 + 2H2O + HCl
Brochantite	Cu4SO4(OH)6	Cu4SO4(OH)6 + 4H2SO4 → 4CuSO4 + 7H2O
Antlerite	Cu3SO4(OH)4	Cu3SO4(OH)4 + 2H2SO4 → 3CuSO4 + 4H2O
Chalcanthite	CuSO4·5H2O	CuSO4·5H2O + H2SO4 → 2CuSO4 + 5H2O

Table 2 /Main Mineralogical Copper Species and Associated Mineralized Zones in Porphyry Copper Deposits/

2.4.1 Acid-Based Leaching of Copper Minerals: Chemical Reactions and Additives

The presented table displays an inclusive lis1 /Main Mineralogical Copper Species and Associated Mineralized Zones in Porphyry Copper Deposits/2t of copper oxide minerals commonly found in copper ore deposits, accompanied by their respective leaching chemical formulas. The leaching process for copper oxide minerals is intricate and requires extensive knowledge of the chemical properties of these minerals to optimize copper recovery. By analyzing the chemical formulas presented in the table, researchers can anticipate the behavior of copper oxide minerals during the leaching process, and can design and optimize the appropriate leaching conditions.

Mineral	Chemical reaction
Bornite (Cu_5FeS_4)	$2Cu_5FeS_4+15O_2+12H_2SO_4$ $\rightarrow 10CuSo_4+2FeSo_4+12H_2O+10SO_2 \rightarrow$
Chalcocite (Cu_2S)	$2Cu_2S+3O_2+2HSO_4 \rightarrow$ $2CuSO_4+2H_2O+2SO_2 \rightarrow$
Chalcopyrite ($CuFeS_2$)	$CuFeS_2+4O_2+16HCl \rightarrow$ $CuCl_2+FeCl_2+2S \rightarrow +8H_2O$
Covellite (CuS)	$CuS+2O_2+2H_2SO_4 \rightarrow CuSO_4 +2H_2O +$ $SO_2 \rightarrow$

Table 3 /Chemical formulas for Copper Sulfide Mineral Leaching/

2.4.2 Leaching types

Leaching is a metallurgical process that involves the selective dissolution of metals or minerals from the ore by means of a chemical solvent. Typically, leaching agents employed for this purpose include acids or bases, although other chemicals may also be used. The leaching process entails the dissolution of the target metal or mineral into the solvent, followed by the recovery of the metal from the resulting solution. Two primary classes of leaching methods are percolation leaching and agitation leaching, which are utilized to extract metals from concentrates. Percolation leaching involves the upward or downward flow of the leaching agent through the ore bed while the ore remains static. Agitation leaching is a highly efficient metallurgical process that facilitates rapid and efficient metal recovery within a shorter time frame. The process typically involves the use of batch, countercurrent, or cocurrent reactors to achieve optimal results. The leaching process is conducted under atmospheric, above atmospheric, or below atmospheric pressures, depending on the specific requirements of the target metal or mineral. Temperature control is critical in the agitation leaching process, and the operating temperature is typically set at ambient or higher levels to optimize the rate of metal dissolution.

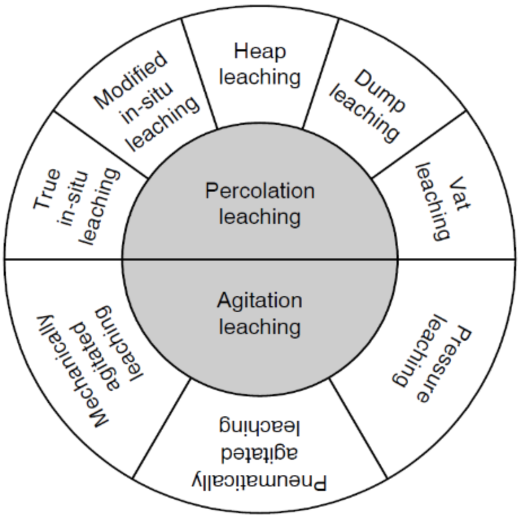


Figure 6 /"Percolation and Agitation Leaching Types" (adapted from Hydrometallurgy Lectures, 2023, p. 6)

2.4.3 Agitation leaching

Agitation leaching is a commonly used process in the mining industry for the extraction of minerals. The process involves mixing ore slurry with a solution in large tanks made of steel and lined with protective materials to prevent corrosion (Adams, 2015). The efficiency of the process depends on various factors, such as particle size, concentration of the solution, temperature, pressure, and the rate of agitation (Kongolo et al., 2019). Increasing the agitation speed enhances the reaction rate by improving mass transfer and increasing the surface area of ore particles exposed to the solution (Yin et al., 2020).

To increase mineral recovery, agitation leaching is often used in combination with other techniques, including heap leaching and carbon adsorption (Akcil & Mudder, 2013). After the leaching process is complete, the remaining ore is purified with chemicals to remove impurities before it is forwarded to a processing plant for further refining (Adams, 2015).

2.4.4 Heap leaching

Heap leaching is a widely used technique in the mining industry for extracting metals from low-grade ore deposits that are not economically viable to mine using conventional methods. The process involves stacking crushed ore on a pad or heap and irrigating it with a leaching solution to dissolve the desired metal. The leaching solution percolates through the heap, collects at the bottom, and is then processed for metal recovery. This method has several advantages over traditional mining methods, such as reduced capital and operating costs, minimized environmental impact, and the ability to process large quantities of ore.

One of the notable examples of a successful heap leaching operation for gold extraction is the Boroo Gold mine in Mongolia. Here, the process involves stacking crushed ore on a lined heap and irrigating it with a cyanide solution to dissolve the gold. The pregnant solution containing gold is collected at the bottom of the heap and further processed to recover the precious metal. A study conducted by Mongolian University of Science and Technology revealed that heap leaching of Boroo Gold mine ore produced a recovery rate of 68.5% to 73.5%, depending on the ore type, which is comparable to the recovery rates achieved through other gold recovery methods.

Heap leaching has helped to reduce the environmental impact of mining operations at Boroo Gold mine by minimizing the need for excavation and reducing the amount of waste generated. The overall efficiency and environmentally friendly nature of the heap leaching the process makes it a viable method for gold extraction at Boroo Gold mine in Mongolia.

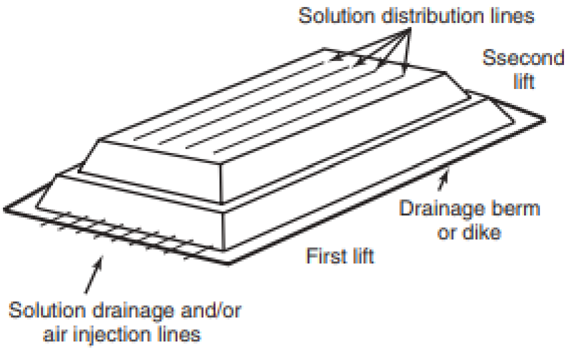


Figure 7 /"Schematic diagram of a typical heap with two lifts" (adapted from Free, 2013, p. 148)/

2.4.5 Dump leaching

Dump leaching has emerged as a popular method for metal extraction, particularly for low-grade ores that have undergone prior processing. Waste rock dumps resulting from copper sulfide mining, for instance, often contain substantial amounts of metal value that can be recovered through this technique. As noted by Ross (2005), dump leaching is implemented in mines worldwide to extract copper and other valuable metals from processed low-grade ores. The process of dump leaching involves irrigating previously processed waste rock or tailings with a chemical solution to extract valuable metals, typically copper. Unlike heap leaching, dump leaching is usually employed on larger piles of waste rock or tailings. The leaching solution is often acidic and generated through the oxidation of sulfide minerals such as pyrite. The solution percolates through the dump to extract copper as copper sulfate, with oxygen being critical to the reaction and supplied to the dump through the interstices between the particles. Bacteria play a significant role in facilitating the leaching reactions, as stated by Lunt and Weeks (2016).Dump leaching offers a cost-effective approach to metal extraction, with no additional processing costs incurred since the overburden does not undergo further size reduction before disposal. However, poor waste management can lead to environmental contamination, which can adversely affect the soil and water quality. As pointed out by Lee et al. (2017), proper management of dump leaching is necessary to prevent environmental contamination. Compared to heaps, dumps are significantly larger and the overburden is directly deposited without any further size reduction, resulting in no additional cost incurred during the leaching process.

2.4.6 In situ leaching

In-situ leaching, also known as solution mining, is a process whereby metal values are extracted from minerals present in an undisturbed ore body in situ, involving the injection of leaching solutions into the ore body, dissolution of metal values by the leachant, and eventual recovery of the pregnant solutions for processing above ground, making it particularly suitable for low-grade ores and offering a specific treatment cost that is considerably lower than that of other leaching techniques, such as those used for gold, silver, copper, and uranium extraction; Successful implementation of this technique requires that the ore body be permeable to the solution and preferably bound by relatively impermeable strata to prevent loss of the solution, as well as being situated below the water table to avoid mixing with natural ground water, which would lead to contamination of groundwater and loss of metal values; if the ore body is not permeable enough, it must be fragmented through the use of explosives, also known as modified in-situ leaching, whereby the process begins with drilling holes into the ore deposit and creating pathways for the solution to penetrate, followed by the injection of leaching solution into the deposit to react with the ore, with the resulting solution containing the dissolved ore content being pumped to the surface for further processing, enabling the extraction of metals and salts from the ore body without the need for conventional mining methods involving drill-and-blast, open-cut, or underground mining.

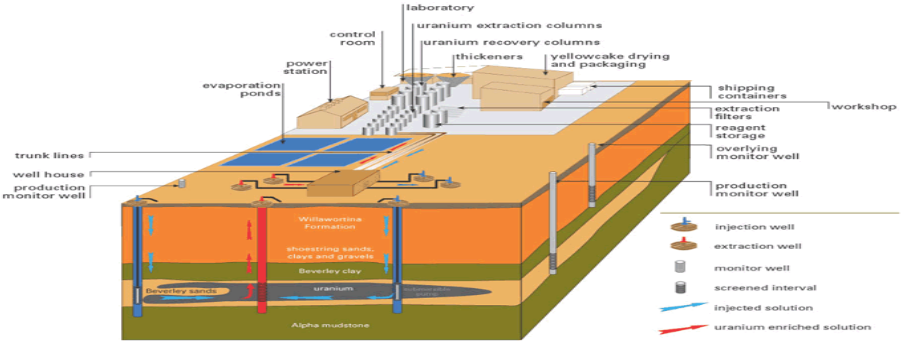


Figure 8 /Pictorial representation of the ISL process (source: Heathgate Resources)/

2.4.7 Vat leaching

The vat leaching process is a method used for the leaching of copper oxide ores with dilute sulfuric acid to produce aqueous copper sulfate solution. This process involves loading the ore into vats made of concrete, which are typically several meters deep and horizontally wide. The vats are equipped with a filter-type bottom to allow for solution flow through the ore bed, and several vats are employed for continuous leaching. Advantages of this process include low solvent consumption, the production of a high-quality leach solution, and the elimination of expensive thickeners or filters. The process is unsatisfactory if much slime is present. Porous and sandy materials are well suited for this process, while materials that tend to pack into impervious masses are not suitable. It is important to use regularly sized particles for good percolation, as unequal-sized particles can cause channels to clog and slow down extraction. The vat leaching process is most effective when the ore is coarse, and the solution is either recycled back into the vat or pumped to the next step of the recovery process. Rectangular containers made of wood or concrete, lined with material resistant to the Leaching media are typically used as vat leach units.

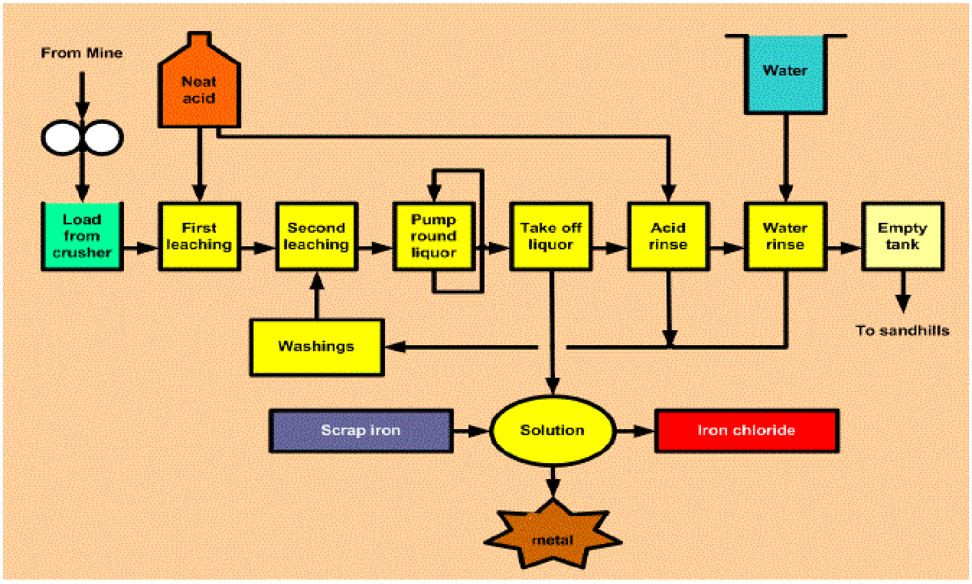
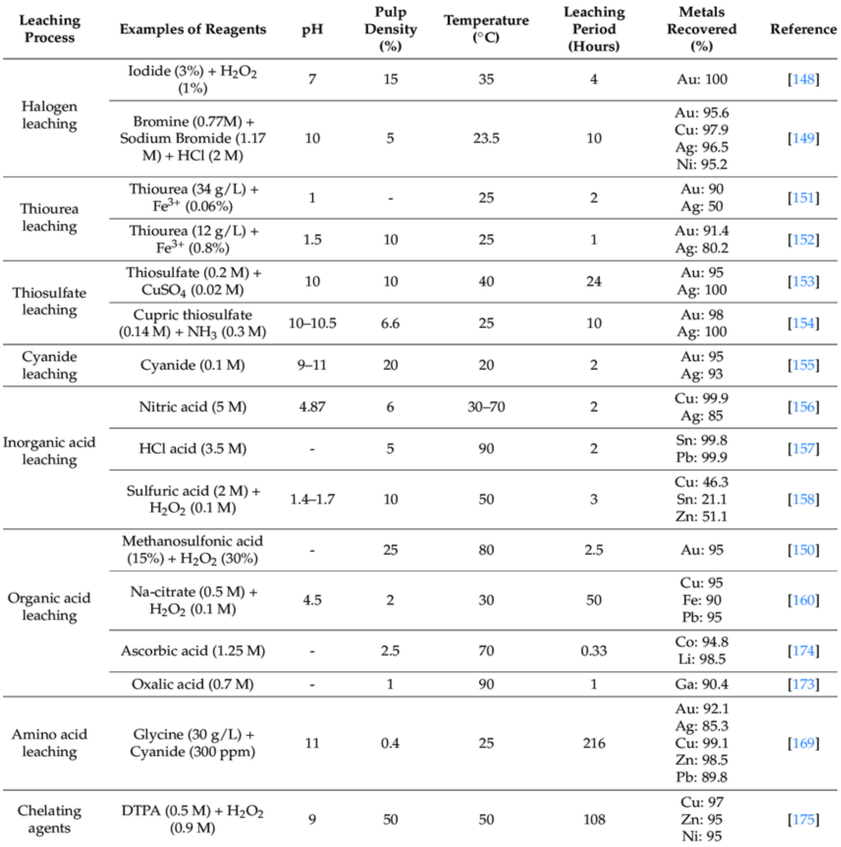


Figure 9 /Procedure to obtain gold: Vat leaching process/

2.5 Characteristic of good lixiviant

The initial stage of the hydrometallurgical processing of minerals involves leaching, which is considered the pivotal unit operation for the economic and technical success of the entire industry. The primary objective of the leaching process is to maximize the valuable metals in the leach solution while achieving the desired characteristics. The selection of the appropriate leach solution is primarily dependent on the mineralogical composition of the ore under consideration. Ascertaining the optimal technical and economic routes for mineral processing necessitates a comprehensive understanding of the ore, particularly its chemical and mineralogical composition, relative proportions of minerals, and particle size distribution. The leaching process is pivotal to the efficient and effective extraction of metals from ores, and the selection of a suitable leach solution depends on an understanding of the mineralogical composition of the ore. An understanding of the ore's characteristics helps in reducing the environmental impact of mining and mineral processing by identifying the most suitable processing route that minimizes waste generation and resource consumption. A understanding of the mineralogical composition ores are critical for sustainable and efficient mineral processing.



Leaching Process	Examples of Reagents	pH	Pulp Density (%)	Temperature (°C)	Leaching Period (Hours)	Metals Recovered (%)	Reference
Halogen leaching	Iodide (3%) + H_2O_2 (1%)	7	15	35	4	Au: 100	[148]
	Bromine (0.77M) + Sodium Bromide (1.17 M) + HCl (2 M)	10	5	23.5	10	Au: 95.6 Cu: 97.9 Ag: 96.5 Ni: 95.2	[149]
Thiourea leaching	Thiourea (34 g/L) + Fe^{3+} (0.06%)	1	-	25	2	Au: 90 Ag: 50	[151]
	Thiourea (12 g/L) + Fe^{3+} (0.8%)	1.5	10	25	1	Au: 91.4 Ag: 80.2	[152]
Thiosulfate leaching	Thiosulfate (0.2 M) + $CuSO_4$ (0.02 M)	10	10	40	24	Au: 95 Ag: 100	[153]
	Cupric thiosulfate (0.14 M) + NH_3 (0.3 M)	10–10.5	6.6	25	10	Au: 98 Ag: 100	[154]
Cyanide leaching	Cyanide (0.1 M)	9–11	20	20	2	Au: 95 Ag: 93	[155]
Inorganic acid leaching	Nitric acid (5 M)	4.87	6	30–70	2	Cu: 99.9 Ag: 85	[156]
	HCl acid (3.5 M)	-	5	90	2	Sn: 99.8 Pb: 99.9	[157]
	Sulfuric acid (2 M) + H_2O_2 (0.1 M)	1.4–1.7	10	50	3	Cu: 46.3 Sn: 21.1 Zn: 51.1	[158]
Organic acid leaching	Methanosulfonic acid (15%) + H_2O_2 (30%)	-	25	80	2.5	Au: 95	[150]
	Na-citrate (0.5 M) + H_2O_2 (0.1 M)	4.5	2	30	50	Cu: 95 Fe: 90 Pb: 95	[160]
	Ascorbic acid (1.25 M)	-	2.5	70	0.33	Co: 94.8 Li: 98.5	[174]
	Oxalic acid (0.7 M)	-	1	90	1	Ga: 90.4	[173]
Amino acid leaching	Glycine (30 g/L) + Cyanide (300 ppm)	11	0.4	25	216	Au: 92.1 Ag: 85.3 Cu: 99.1 Zn: 98.5 Pb: 89.8	[169]
Chelating agents	DTPA (0.5 M) + H_2O_2 (0.9 M)	9	50	50	108	Cu: 97 Zn: 95 Ni: 95	[175]

Figure 10 / Overview of leaching agents used in hydrometallurgy as well as the process conditions (E-Waste Recycling and Resource Recovery publication) /

2.5.1 Glycine as copper lixiviant

Glycine, or 2-aminoacetic acid, is classified as the most elementary member of the amino acid family due to its molecular structure. As denoted by their name, amino acids are composed of both an amino group (-NH2) and a carboxyl group (-COOH) that are covalently linked to the same α-carbon atom. The distinct properties of each amino acid are determined by their side chains, represented by the variable R. For instance, Glycine has a simple hydrogen atom as a side chain (H2N-CH2-COOH) that governs its unique properties (de Farias et al., 1999).

The properties of glycine can be described in the following manner: (Tanda 2017, p.38)

- Colorless, sweet crystalline solid in pure form.
- High melting point of 262 C and decomposition point 292C.
- Soluble in water (25g/100ml at 25 C), acids, alkalis but not soluble in organic solvents

Glycine has been utilized in various industrial fields, showcasing its versatility and wide range of applications:

- Taste enhancer and sweetener in food production
- Pharmaceuticals and medicine in intravenous injections
- Buffering agent in cosmetics
- Leveling agent in acidic electroplating of Cu(Aksu & Doyle, 2001) and Zn-Fe (Karahan,

2013) to produce smoother deposits by modifying the structure and topography

Aqueous chemistry of glycine (Tanda BC,2017)

Glycine displays amphoteric properties in aqueous solutions, acting both as an acid (proton donor) and a base (proton acceptor), which depend on the pH of the solution. In solutions with a pH below 2.35, the glycinium cation + H3N CH2 COOH (H2L) is the dominant form. The zwitterion + H3NCH2COO- (HL) is the stable form between pH values of 2.35 and 9.78, and when the pH exceeds 9.78, the glycinate anion H2NCH2COO- (L) becomes predominant.

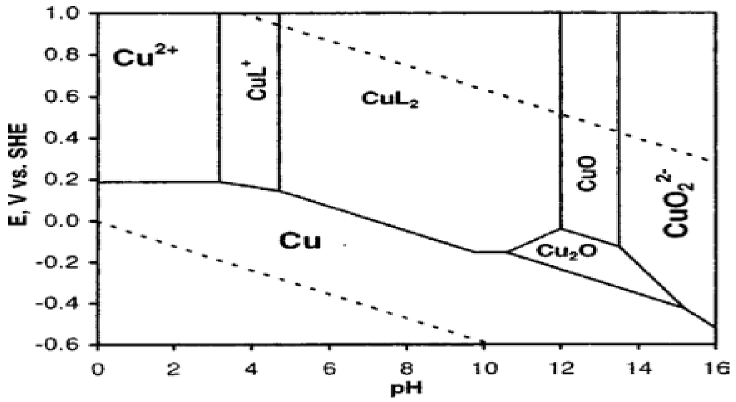


Figure 11 /Eh-pH diagram for copper-water-glycine system at a total dissolved copper activity of 10^{5} and total glycine activity of 10^{2} at 25 C and 1 atm (Aksu, 2003)/

Aqueous Chemistry of copper and glycine

Copper ion	**Copper-glycine complex**	**logK**
Cu^{2}+	$Cu(H_2NCH_2COO)_2$	15.6
Cu+	$Cu(H_2NCH_2COO)_2$-	10.1
Cu^{2}+	$Cu(H_2NCH_2COO)$-	8.6

Table 4 /Copper glycine complexes and their stability constants (Aksu, 2001)/

Table above shows that the stability constants of glycinate complexes of Cu(I) and Cu(II) have been determined. In biological systems, the copper glycinate complex has been detected, particularly in enzymes, where it functions in active sites. This observation has spurred extensive research aimed at elucidating the underlying mechanisms that govern the interaction between cupric ions and amino acids, which act as intermediaries for the transport of copper in living organisms (Bukharov et al., 2014).

3.Materials and method

3.1 Chapter objective

The present thesis has utilized diverse materials and research methodologies with the purpose of achieving its objectives. The primary goal of this section is to provide an exhaustive account of the materials, equipment, and analytical procedures that were employed throughout this study.

Central aim of this research endeavor is to scrutinize the leachability of oxidized copper ore in both conventional and novel leaching processes. In order to accomplish this goal, an assortment of minerals and ores samples were subjected to various experimental procedures, which are comprehensively explicated in this chapter. The techniques employed for sample characterization and preparation, as well as the apparatus and operating conditions utilized for the experiments, are elaborated upon in detail.

Agitation tank leaching method was implemented to evaluate the ore, with glycine and sulfuric acid serving as the main lixiviants. It is hoped that this research will contribute to a better understanding of the leaching behavior of copper ores and will pave the way for the development of more efficient leaching processes. In essence, this chapter outlines the fundamental principles of the different techniques that were employed to gather the necessary data for the leaching experiments.

The experimental parameters, conditions , and various procedures for sample preparation are described in great detail, along with the process of leaching oxidized copper ores in the agitation tank. These topics are further elaborated upon in subsequent sections, providing a thorough understanding of the methodology employed in this research.

3.2 Materials and reagents consumption

In the preparation of the primary luxuriant alkaline glycine and sulfuric acid solutions, the molar ratio of glycine to copper was carefully considered, with analytical-grade reagents being utilized exclusively. Specifically, all reagents employed in this study were of analytical purity, and none were of a lower quality. Furthermore, a detailed list of the copper ore samples employed in the experiments was provided in Table 5,Table 6 along with a comprehensive inventory of the analytical-grade reagents and gasses used in the various trials described in this thesis.

A comprehensive list of the phase compositions of oxidized copper ore originating from Oyu Tolgoi LLC is presented, serving to further augment the findings of this study. The collaboration between GMIT and Oyu Tolgoi LLC enabled the procurement of Geomet 1, Geomet 2, and Geomet 6 oxidized copper ore samples, with Geomet 6 serving as the specific oxidized copper ore utilized in this study. It should be underscored that the samples obtained were of the highest quality and were meticulously handled in accordance with the prevailing analytical guidelines.

№	Reagent	Chemical formula	Purpose	Purity
1	Glycine	H_2NCH_2COOH	Main lixiviant	AR
2	Sulfuric acid	H_2SO_4	Main lixiviant	AR
3	Air	-	Optimization	Atmospheric
4	Copper(||) sulfate	$CuSo_4$	Spectrum test	98%

Table 5 /This study utilized a range of analytical grade reagents and gasses, which are listed below/

Element	Cu	Fe	S	Zn	Al	Ba	P	Si	K	Ca
%	0.527	2.74	0.801	0.005	11.4	0.062	0.115	23.15	2.22	0.083

Table 6 /Results were generated from data collected via the X-ray Fluorescence (XRF) test conducted prior to the experiment.t/

3.3 Experimental equipment & apparatus

3.3.1 Comminution equipments

The sample received from "Oyu Tolgoi" LLC contained numerous large particles measuring around 100-300mm. In order to prepare the sample for leaching experiments with optimal particle sizes, various comminution techniques were employed. This included the use of a jaw crusher, cone crusher, and rod mill during the sample preparation process.

The German-Mongolian Institute for Resource and Technology's jaw crusher, 5E-JCA150x125, has a maximum standard inlet for feed particle size of 150x125 mm, with an allowable particle size for feeding of up to 100mm. To begin the comminution process, the sample was first crushed by the jaw crusher into particles with a size of $P100<$ 36mm, using it as the primary crusher. The crushing size can be adjusted and ranges between 6-36 mm.

For the leaching behavior experiments, a total of 15kg of ore was used and crushed into particles with a size of $P80< -6$ mm using a jaw crusher. Subsequently, the crushed ore was further comminuted using an XPC200 Laboratory Double Roller Cone Crusher until it reached a particle size of $P80< -2$mm.

To achieve the desired particle size for the leaching experiments, a rod mill was employed as the final milling process. The milling process lasted for 15 minutes with a rotation speed of 17Hz, until 90% of the particles passed $P80 < -75$um. In total, 12 rods were used during the milling process, with a total weight of 16.7kg.

Figure 12 / Jaw crusher/

Figure 13 / Cone crusher/

3.3.2 Sieving apparatus

To ensure the uniform distribution of particle size of the ore for agitation tank leaching tests, a stainless steel automatic apparatus was used to conduct sieve analyses on the output of the rod mill. The sieve analysis focused on particles with a size of P80<−75um.

In order to ensure accurate leaching experiments, a stainless steel automatic apparatus equipped with various sieve sizes (0.5mm, 0.312mm, 0.3mm, 0.15mm, 0.106mm, and 0.075mm) was utilized to conduct an analysis for determining the even distribution of particle size. This methodology was designed to minimize potential sources of error and produce precise and consistent results. The results of the analysis were further utilized to generate the Gates-Gaudin-Schumann graphs, providing valuable insights into the even distribution of particle size.

Figure 14 /automatic sieve apparatus/

Figure 15 / Controller of automatic sieve apparatus/

The automatic sieve apparatus was set up to conduct dry sieving for a duration of 10 minutes at 80 amplitude.

3.4 Agitation tank leaching apparatus

The XJT(2) leaching mixer, is well-suited for conducting scientific research and experimentation in the area of leaching. This apparatus boasts of a high-speed rotating rotor that generates centrifugal force, propelling the liquid out of the rotor.The inclusion of an air pump facilitates the production of small mineralized bubbles, which ensure an efficient mixing process.

To ensure a high degree of accuracy during experimentation, the XJT(2) leaching mixer is equipped with a temperature control meter, which allows for precise temperature regulation during the leaching process. The apparatus is constructed using high-quality materials, including a base frame, impeller, sleeve stirring tank, bearing seat, motor, and switchboard, ensuring a robust and durable design.

It was important to note that the impeller must rotate in a clockwise direction to optimize performance. The agitation tank leaching apparatus employed in the experiments was fitted with three impellers, with a Φ39 impeller being selected for the experimentation. and the apparatus was outfitted with three different volumes of stirring tanks (5L, 3L, 1L), enabling the selection of an appropriate impeller and stirring tank based on the sample volume and solid-liquid ratio.

XJT(2) leaching mixer and the agitation tank leaching apparatus were crucial to the success of the experimentation process. Their ability to set the regulated temperature and efficient mixing was essential in ensuring accurate and reliable results.

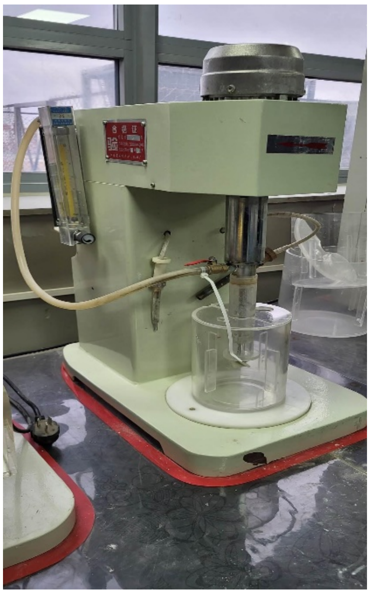


Figure 16 / Agitation tank leaching apparatus XJT/

Figure 17 / Control panel of the apparatus/

3.5 Experimental procedures

3.5.1 Sample preparation

During the leaching investigation, the copper ore received by the German-Mongolian Institute for Resources and Technology (GMIT) from "Oyu Tolgoi" LLC was analyzed. The ore's particle size was found to be excessively large, which necessitated its processing through a primary crushing device (jaw crusher) to achieve a P80 < -36mm size, followed by further crushing with a cone crusher to obtain a P80 < -2mm size. Total 15kg of ore was taken from Geomet 6 copper ore and separated into 2 parts, with 5kg reserved for emergency purposes in case of experimental failure. Remaining 10 kg of ore investigated further processes was mixed thoroughly using shoveling to ensure uniform distribution. But P80 < -2mm copper ore size for leaching and mineral analysis was too coarse, therefore a rod mill was employed. Determining the appropriate grinding conditions was critical, and a 10kg well-mixed ore sample was utilized to identify optimal grinding conditions. Subsequently, three trials were conducted using 1kg of ore for each trial to determine the ideal grinding time. After conducting the three grinding trials for 5, 10, and 15 minutes, respectively, the most suitable grinding time for achieving the desired particle size was determined. To ensure that the ore particles were of the appropriate size, dry sieving was performed, and the 15-minute grinding trial was deemed optimal since 90% of the particles passed through a P80< 75 um sieve.Upon finishing the crushing and grinding processes, 7kg of ore mixed thoroughly using shoveling to ensure uniform distribution. To obtain a representative sample of the entire ore, the well-mixed sample underwent the coning and quartering method, leading to equal parts. One of the parts was further subdivided using the same method until a 1kg sample was obtained, which was considered to represent the ore. This sample underwent head assays via X-ray Fluorescence (XRF) at the laboratory, a technique that identifies the mineral sample's elemental composition. Table 6 shows the results of the copper and other mineral data acquired from the XRF analysis.

Figure 18 / X-ray Fluorescence (XRF) gun /

XRF gun that used this investigation and analyzation of copper ore was handheld device that apply X-ray fluorescence spectroscopy for non-destructive material analysis. The mechanism of this technology is based on the interaction of X-rays with the atoms in a material, which generates fluorescent X-rays with distinct energies attributed to the specific elements present. By measuring these X-rays, XRF guns are capable of quantifying the concentrations of diverse elements in various materials, such as metals, alloys, plastics, ceramics, and more. These devices are commonly employed in applications like quality control, materials testing,. Before using an XRF gun, it was necessary to prepare and set the device's suitable conditions for the material to be analyzed. For instance, in this case of Cu/Zn analysis, the device should be held for approximately 38-41 seconds before the results displayed.

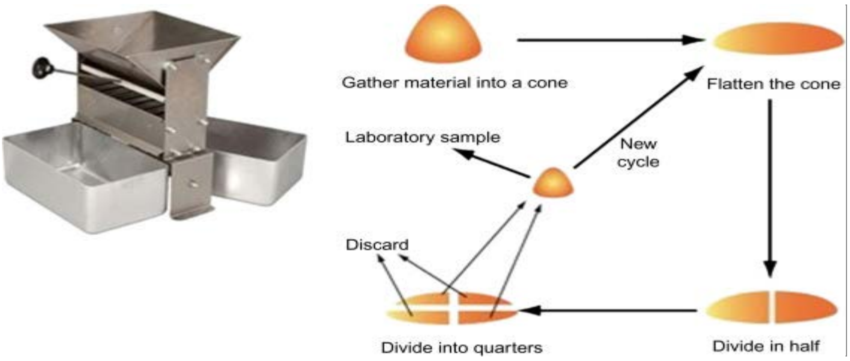


Figure 19 / (Left) Jones sample splitter, (right) sketch of coning and quartering method of sample preparation. Source: Courtesy: Jacob./

Agitation tank leaching test sample preparation

To conduct agitation tank leaching experiments on copper ore, a total of 36 experiments were planned. The 5400kg ore sample was divided into 36 equal parts of 150g each, with a particle size of P80 < -75um for each part. The sample separation process utilized techniques of splitting that ensured equal size and concentration . For a visual representation of the process refer to the figure 18 above.

3.5.2 Investigation of the leaching behavior copper ore through agitation tank leaching

The primary objective of these experiments was to investigate the copper ore's leaching behavior under varying conditions, including different reagents at different concentrations and varying levels of agitation and aeration. The results obtained from these experiments can provide valuable insights into the leaching mechanism of copper ore, enabling the optimization of leaching processes and the development of more efficient and sustainable methods for copper recovery. The agitation tank leaching method was chosen for the leaching experiments due to its ability to manipulate various parameters, such as air flow and stirring speed, to optimize leaching efficiency. By adding air bubbles during leaching, the agitation tank allows for improved mass transfer between the ore particles and leaching solution, leading to more efficient extraction of the target minerals. Additionally, the stirring speed can be adjusted to maintain a homogeneous mixture and prevent settling of particles, ensuring that the leaching solution is in contact with all available surfaces of the ore.The leaching experiments employed two main types of solutions as lixiviants, reagent grade glycine and sulfuric acid, which were prepared accordingly. These solutions were utilized to investigate the leaching behavior of copper ore under varying conditions.

The solid phase of the copper ore has a copper content of 0.527%. For the experiment, approximately 115g of the cut-off grade ore was weighed. The sample was then placed into the agitation tank vessel, along with a leaching solution containing sulfuric acid and glycine. The solid-to-liquid ratio for the leaching experiment was 30:70 (150g ore / 350g liquid), for a total of 500g.The experiment was initiated by preparing a concentrated solution of glycine and sulfuric acid, which was then diluted with 70g of water. Next, 70g of the diluted solution was added to 280g of water to obtain a total liquid volume of 350g with a solid-to-liquid ratio of 30:70. Finally, 150g of grinded solid ore material was added to the liquid solution for the leaching experiment to proceed. To minimize the margin of error in the results, all experiments were conducted three times for each duration of 15, 30, 60, and 90 minutes. The study involved 36 trials that varied in the concentration of glycine/sulfuric acid, along with two different stirring speeds of 1257rpm and 2514rpm, while maintaining the temperature at ambient levels and the airflow at 2.

The leaching behavior experiments using agitation tank leaching were conducted in two parts. In the first part, sulfuric acid was used as a lixiviant with varying concentrations of 0.1M, 0.25M, and 0.4M, and two different rotation speeds of 1257rpm and 2514 rpm were tested for each concentration. The second part of the experiment involved the use of comparison glycine as the lixiviant with the same concentrations as sulfuric acid, and the same two different rotation speeds were used for each concentration. At intervals of 15 min, 30min, 60min, and 90min, the agitation tank leaching experiment was stopped to collect the solution, and the pH was measured.

To determine the appropriate concentration of sulfuric acid for the leaching of copper ore, the molar ratio of sulfuric acid to copper molar weight was calculated, resulting in a concentration of 0.0186M. However, other minerals in the copper ore also dissolve during leaching, leading to an increase in the actual concentration of sulfuric acid used in the experiment by a factor of 5.4. Therefore, to investigate the effect of sulfuric acid concentration on the leaching behavior of copper ore, concentrations of 0.1M, 0.25M, and 0.4M were used, along with the same concentrations of glycine as a comparison lixiviant. The total amount of sulfuric acid and glycine used was equal to 130.2g and 116.4g, respectively.As previously mentioned, during the time intervals when the agitation leaching was stopped to collect solution samples for UV/VIS spectrophotometer testing, the slurry solutions were filtered using a vacuum filtration process. The agitation tank leaching tests were carried out under different conditions to determine the leaching behavior of copper ore, as shown in Tables 7-9.

Investigation of Sulfuric Acid Concentrations on Copper Ore Leaching							
№	Name	Particle size	Sulfuric acid concentration	Copper present	Weight of ore	Air	Stirring speed
1	Test 1	<90 % 75 micron	0.1M	0.527 %	150g	flow rate of 2 unit	1257 rpm
2			0.25M				
3			0.4M				

Table 7 /Test 1. Effect of sulfuric acid concentration test on copper ore/

Investigation of Sulfuric Acid concentrations on Copper Ore Leaching							
№	Name	Particle size	Sulfuric acid concentration	Copper present	Weight of ore	Air	Stirring speed
4	Test 2	<90 % 75 micron	0.1M	0.527 %	150g	flow rate of 2 unit	2514 rpm
5			0.25M				
6			0.4M				

Table 8 /Test 2. Effect of sulfuric acid concentration test on copper ore with different rotation speed/

Investigation of Glycine concentrations on Copper Ore Leaching							
№	Name	Particle size	Glycine concentration	Copper present	Weight of ore	Air	Stirring speed
7	Test 3	<90 % 75 micron	0.1M	0.527 %	150g	flow rate of 2 unit	1517 rpm
8			0.25M				
9			0.4M				

Table 9 /Test 3 Effect of glycine concentration test on copper ore/

Investigation of Glycine concentrations on Copper Ore Leaching							
№	Name	Particle size	Glycine concentration	Copper present	Weight of ore	Air	Stirring speed
10	Test 4	<90 % 75 micron	0.1M	0.527 %	150g	flow rate of 2 unit	2514 rpm
11			0.25M				
12			0.4M				

Table 10 /Test 3 Effect of glycine concentration test on copper ore with different rotation speed/

The investigation of the leaching behavior of copper ore using different lixiviants involved 36 experiments with each test repeated three times over 54 hours, as previously mentioned. A total of 144 samples were collected from these experiments to determine the copper concentration in the solution using UV/VIS spectrophotometry and calculate the metal recovery. After leaching with 0.1M glycine, a noticeable change in the color of the solution was observed, which appeared brighter than the color of the solution leached with 0.1M sulfuric acid. As a result, it is expected that the metal recovery from the glycine leaching solution would be better than that of the sulfuric acid leaching solution. Figure 19 shown below.

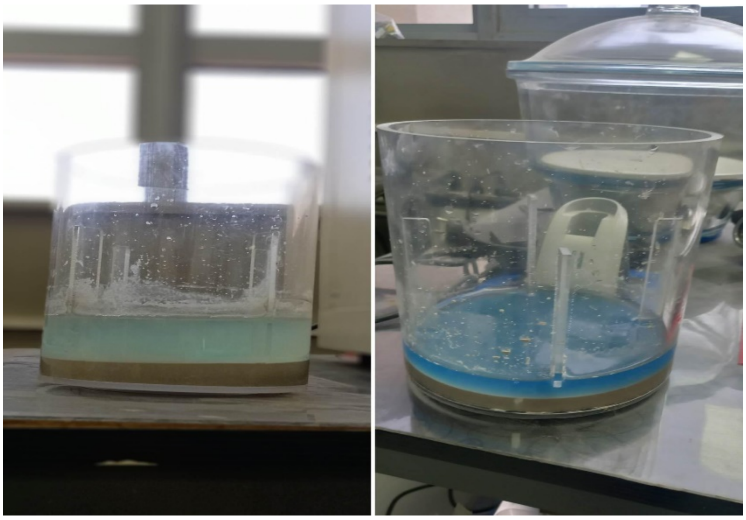


Figure 20 /Color comparison of 0.1M sulfuric acid leaching solution and 0.1M glycine leaching solution/

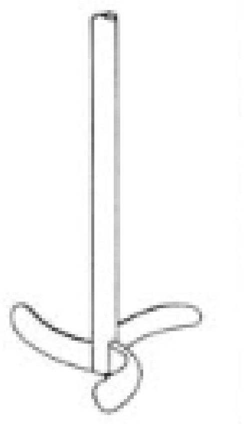


Figure 21/ Flow pattern of the stirring impeller in the tank reactor. Adapted from "Chemical Reaction Engineering Lecture 3: Tank Reactors," by Prof. Dr.-Ing. Manfred J. Hampe, 2023, Chemical Reaction Engineering Course./

The figure 19 and 20 depict that the agitation tank leaching apparatus in our raw material and process engineering laboratory is a type of batch reactor, particularly a tank reactor. Its quick production and flexibility support this fact, along with the absence of input and output, which further strengthens its similarity.

One of the critical components of agitation tank leaching equipment is the presence of baffles in the vessels. Baffles play an essential role in preventing the occurrence of Gabriel's Horn or Torricelli's Trumpet. Additionally, in tank reactors, baffles ensure efficient and uniform mixing of reactants, prevent the formation of dead zones and vortices, and increase residence time.

4. Result and Discussion

4.1 Chapter objectives

The main objective of this chapter is to examine the leaching behavior of copper ore in glycine and sulfuric acid solutions at ambient temperature, particularly by utilizing agitation tank leaching. Additionally, this chapter includes a comparative analysis of the new and conventional leaching reagents, as well as discussions on impurity dissolution and particle size distribution. The mineralogical XRF test was conducted after the agitation tank leaching tests.

The objective of the agitation tank leaching tests was to investigate the effects of reagent concentration, pH, and optimization parameters. Air was utilized for oxidation during the leaching experiments, with a flow rate of 2 units. Although various temperature parameters were initially planned to be tested using the equipment's temperature controller, operational issues prevented these tests from being conducted, and the temperature was set to ambient instead.

Initially, mineralogical analyses were intended to be conducted in the laboratory to identify the mineralogical phase of the copper ore. However, instead, an XRF gun was utilized to perform elemental analysis on the materials used in the copper ore, revealing a pure copper grade of 0.527%.

The original plan was to conduct mineralogical analyses in the laboratory to determine the mineralogical phase of the copper ore. However, due to unforeseen circumstances, this was not possible. Therefore, an XRF gun was utilized to perform elemental analysis on the materials used in the copper ore, which showed a pure copper grade of 0.527%. Based on this data, it can be assumed that copper-bearing minerals such as chalcopyrite, bornite, chalcocite, and cuprite are present in the ore. However, without further mineralogical analysis, it is challenging to determine the exact mineral composition.

4.2 Result of leaching behavior of copper mineral bearing ore

4.2.1 Effect of sulfuric acid concentration of copper ore

The experiments started with 0.1M 0.25M 0.4M concentrations while varying the rotation speed of stirring. The results, presented in Figure 22-24, demonstrate that the increase of a rotation speed had a significant impact on copper recovery rates over time.

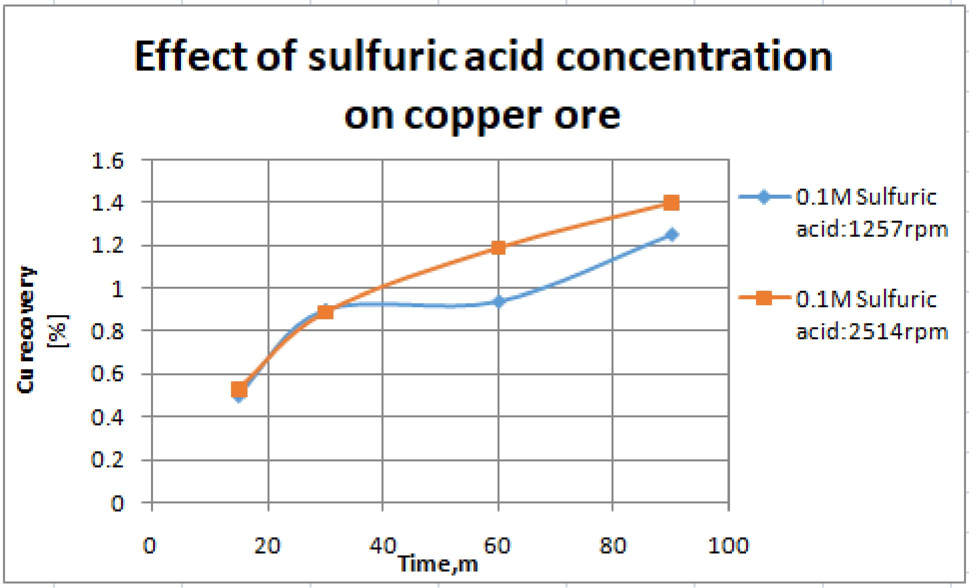


Figure 22 /Effect of 0.1M sulfuric acid concentration of copper mineral bearing ore/

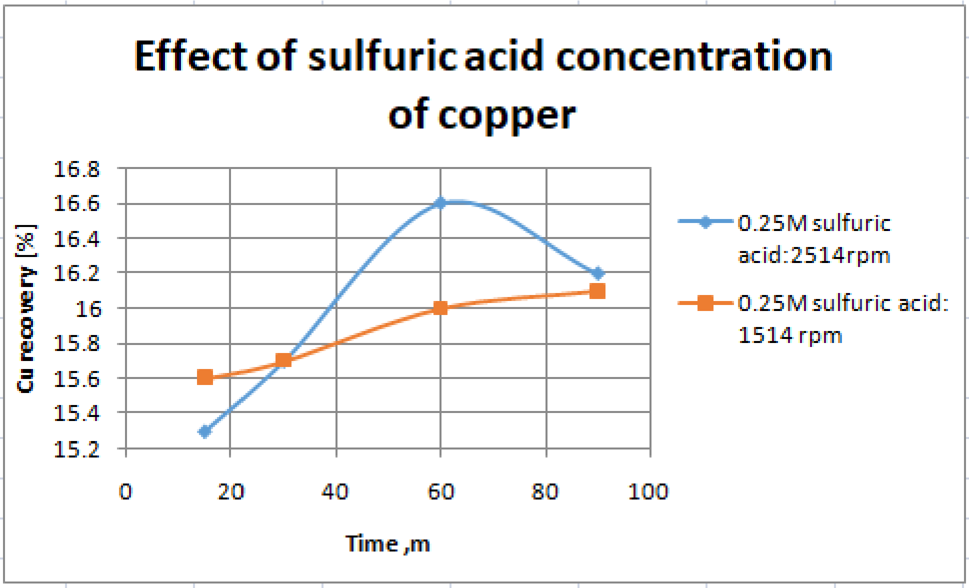


Figure 23 /Effect of 0.25M sulfuric acid concentration of copper mineral bearing ore/

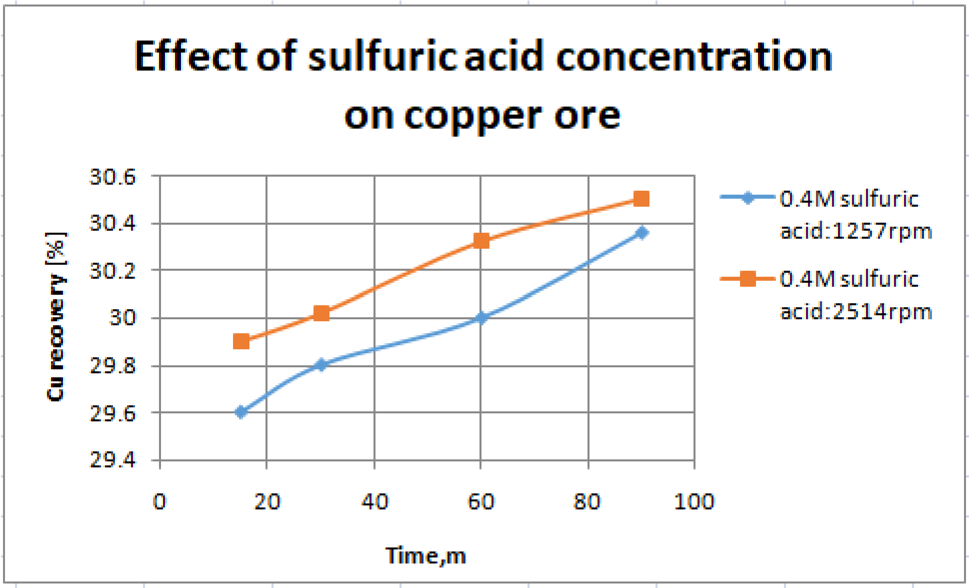


Figure 24 /Effect of 0.4M sulfuric acid concentration of copper mineral bearing ore/

Higher rotation speeds were found to lead to increased copper recovery rates, underscoring the importance of optimizing stirring conditions to improve the efficiency of the leaching process. These findings suggest that further optimization of the leaching process could lead to even greater efficiency gains. Notably, air was used as an optimization method during these experiments (2 flow rate units) . The metal recovery values shown in the graphs represent the average of three separate tests, with further details available in the Appendix.

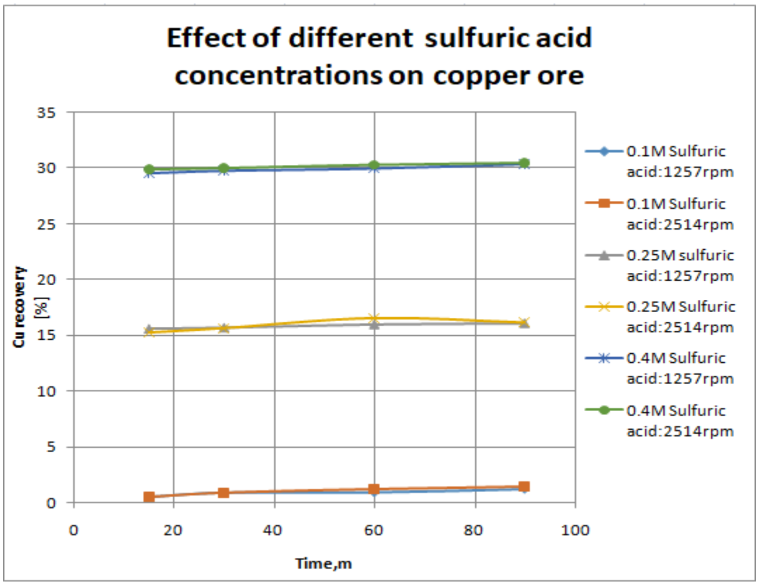


Figure 25 /Sulfuric acid solutions in different concentration/

The graph illustrates that as the concentration of the leaching solution sulfuric acid increases, there is a corresponding increase in the recovery of copper. The values depicted on the graph represent the average results obtained from three separate tests.

4.2.1.1 Comparison of pH values in solutions of different sulfuric acid concentrations for leaching process optimization

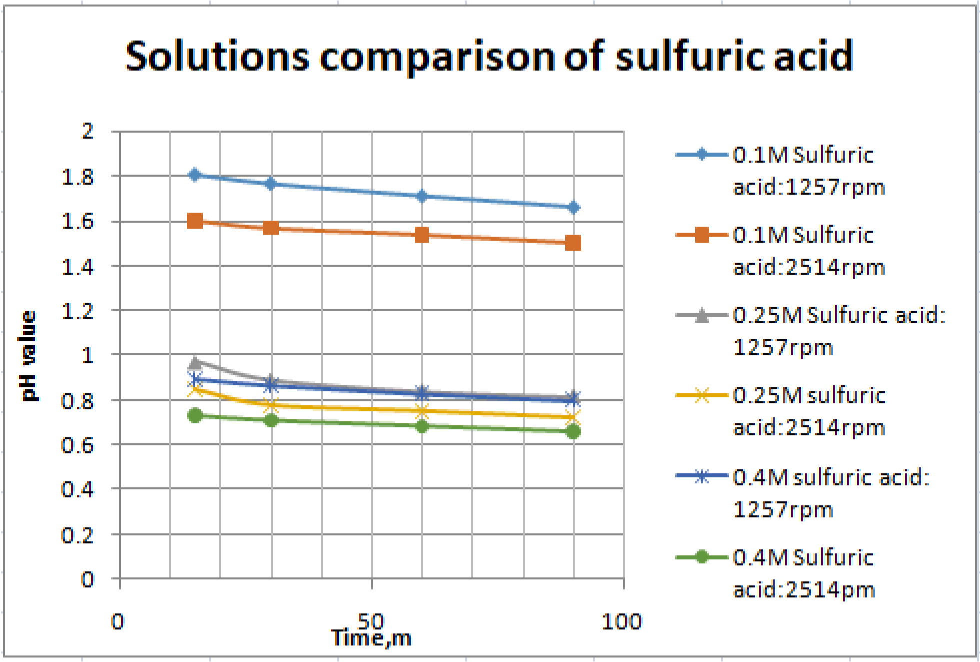


Figure 26 /Comparison of pH values in different sulfuric acid concentrations/

During the agitation tank leaching test, pH measurements of the sulfuric acid used as a leaching reagent were taken during the sample collection process. A total of 72 solutions were collected at different time intervals, and the pH values were recorded and presented in Figure 26. The results indicate that the pH values of the solutions decreased over time intervals.

4.2.2 Effect of glycine concentration in copper ore

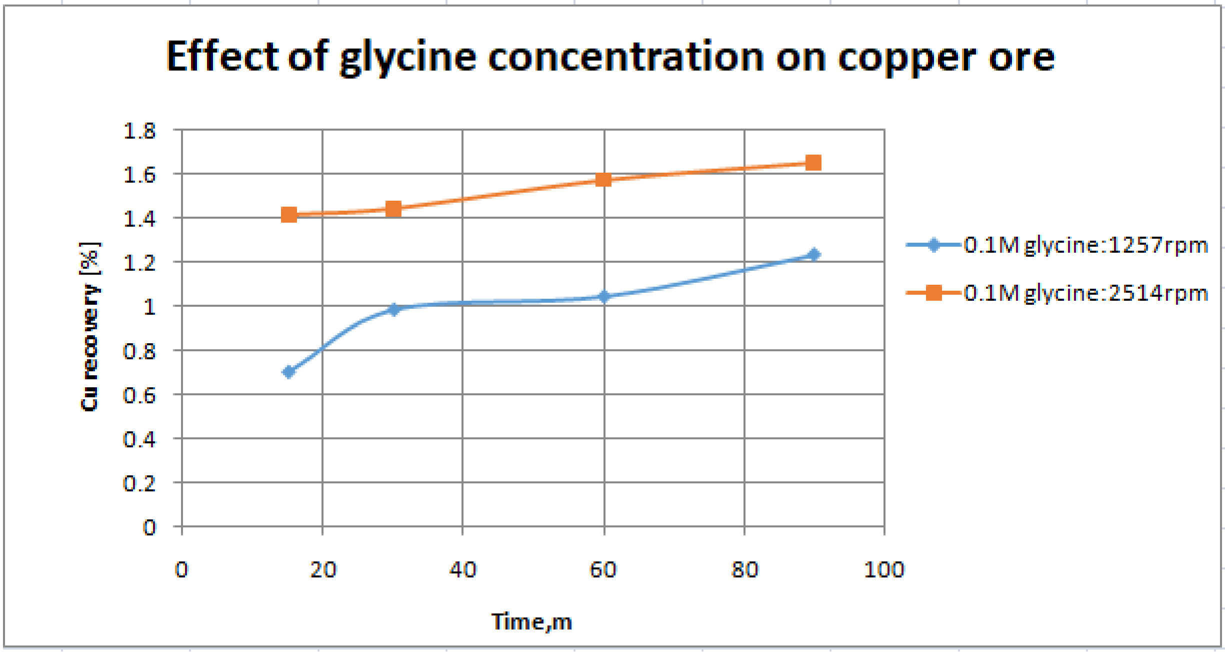


Figure 27 /Effect of 0.1M glycine concentration of copper mineral bearing ore/

The effect of glycine concentration tests was conducted on copper-bearing mineral ores during leaching, and pH values were observed to increase at different times. Therefore, pH values were not kept constant throughout the experiment. Based on the results, it can be concluded that increasing glycine concentration leads to higher copper recovery, as shown by the graph. However, the optimum concentration and other factors affecting the leaching process should be further investigated for practical applications.

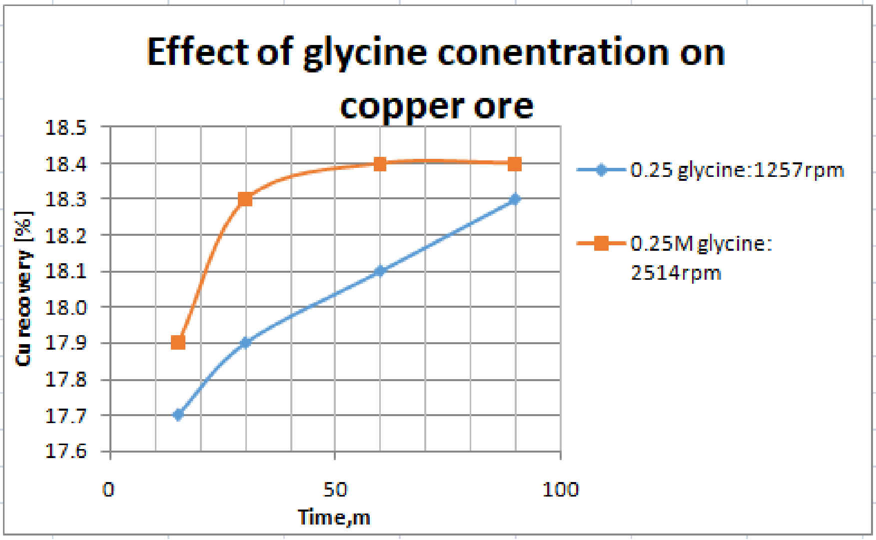


Figure 28 /Effect of 0.25M glycine concentration of copper mineral bearing ore/

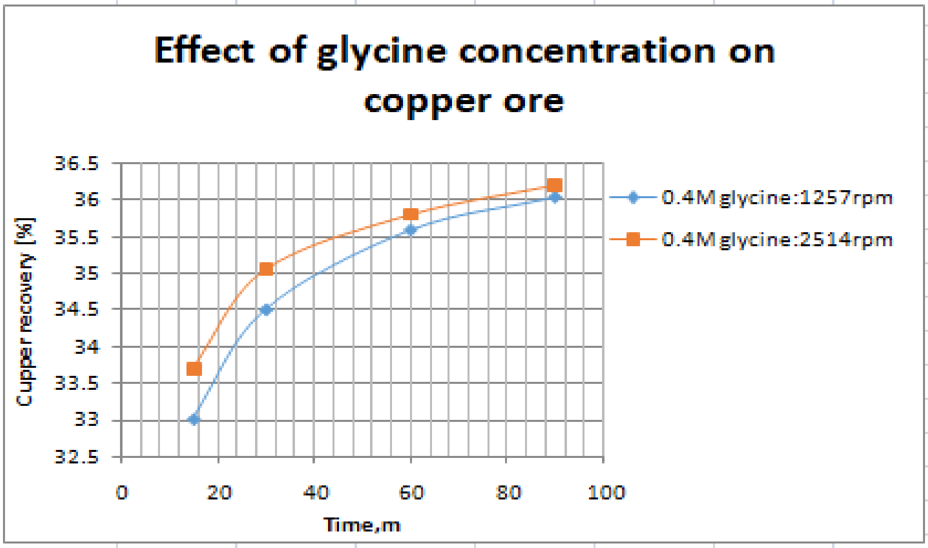


Figure 29 /Effect of 0.25M glycine concentration of copper mineral bearing ore/

The effect of glycine concentration tests was conducted on copper-bearing mineral ores during leaching, and pH values were observed to increase at different times. Therefore, pH values were not kept constant throughout the experiment. Based on the results, it can be concluded that increasing glycine concentration leads to higher copper recovery, as shown by the graph. However, the optimum concentration and other factors affecting the leaching process should be further investigated for practical applications.

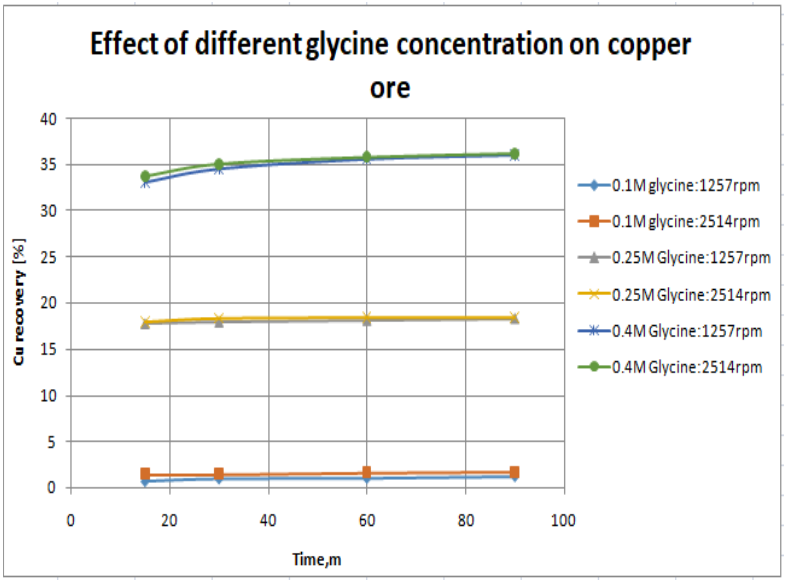


Figure 30/Glycine solutions in different concentration/

Based on the data presented in the graph, it can be observed that in the 0.1M glycine experiment with 2514 rpm rotation speed, the difference between the first two plotted values is relatively small, whereas the subsequent plotted values exhibit a gradual increase. Moreover, in the 0.1M glycine experiment with 1257 rpm rotation speed, there is not a significant difference between the second and third plotted values. From these the concentration of glycine and the rotation speed of the agitation tank can have a significant impact on the copper recovery rate in the leaching process.

4.2.2.1 Comparison of pH Values in solutions of different Glycine concentrations for leaching process optimization

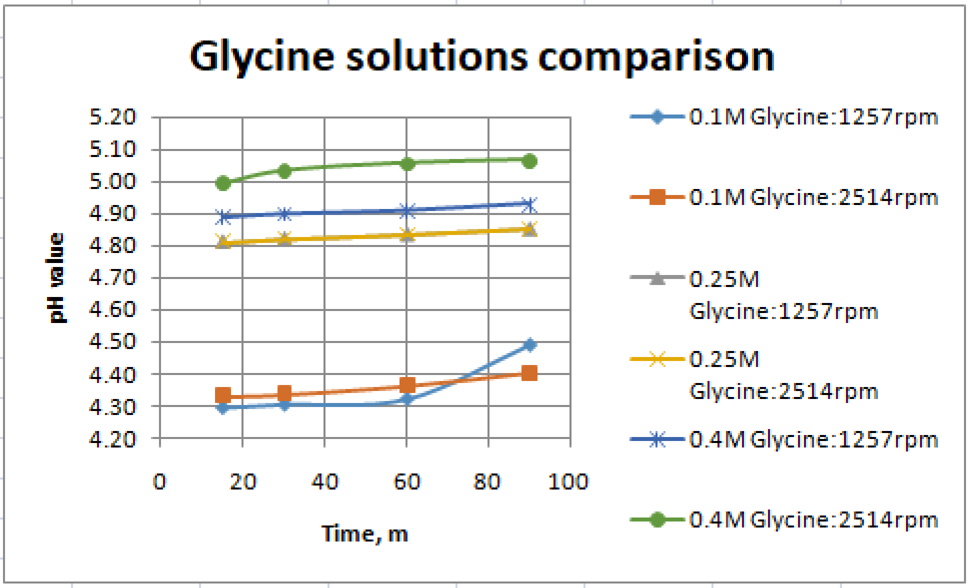


Figure31/Comparison of pH values in different sulfuric acid concentrations/

In the agitation tank leaching test, pH values of the Glycine reagent were measured during the sample collection process. A total of 72 solutions were taken at different time intervals, and the pH values were recorded and shown in Figure 31. The data indicate that the pH values of the solutions increased over time intervals.

4.3 Comparative Analysis of Sulfuric Acid and Glycine Agitation Tank Leaching Solutions for Copper Mineral Bearing Ore

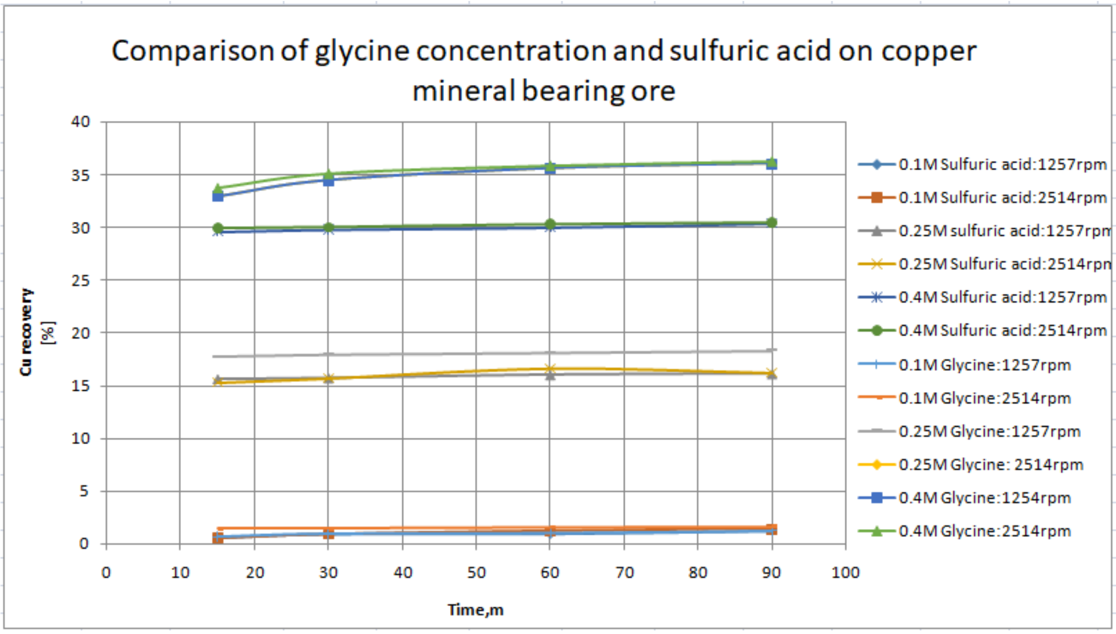


Figure 32 /Comparison of glycine concentration and sulfuric acid on copper mineral bearing ore/

The data in Figure 23 illustrate the leaching performance of copper-bearing mineral ore using alkaline glycine and sulfuric acid as leaching agents. The ore sample contained 0.527% copper and three different concentrations of each leaching agent were used. It is noteworthy that the concentration of the two lixiviants was kept constant and equal in the experiment.

Based on the data presented in the figure, it is evident that the leaching behavior of copper-bearing mineral ore in alkaline glycine is more efficient compared to the conventional leaching agent sulfuric acid. This is indicated by the higher recovery percentage of copper in glycine solutions compared to sulfuric acid solutions. It should also be noted that the leaching process tends to react with a wide range of impurities such as iron, silicon, magnesium, calcium, and aluminum, as shown in Table 6, which indicates the initial values of these minerals. Therefore, using glycine as a leaching agent could potentially improve the efficiency of copper recovery while also reducing the amount of impurities extracted from the ore.

4.3.1 Optimizing Leaching Process: Comparison of pH Values in Solutions with Different Sulfuric Acid and Glycine Concentrations

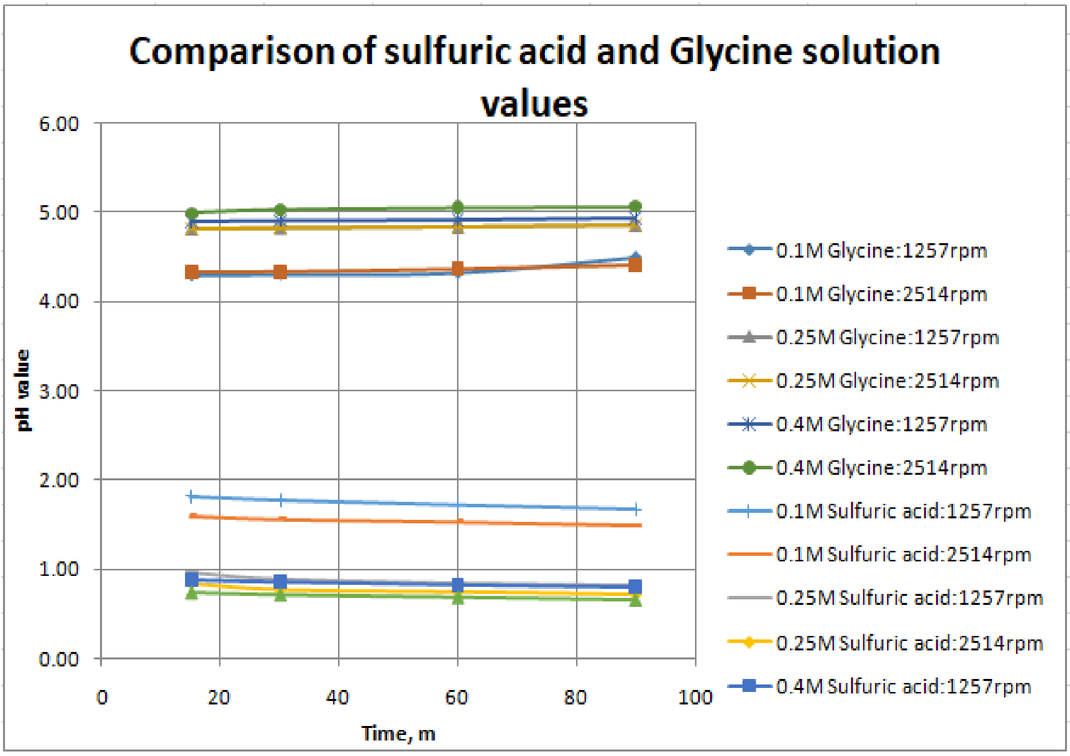


Figure 33 /Comparison of pH values of glycine and sulfuric acid solutions/

As shown in Figure 33, the pH of the sulfuric acid leaching reagent decreased over time intervals, while the pH of the glycine leaching reagent increased over time intervals. These pH changes are due to the different chemical properties and reaction mechanisms of the two reagents with the ore. Sulfuric acid acts as an acidic reagent, releasing hydrogen ions (H+) into the solution and resulting in a decrease in pH over time. On the other hand, glycine is a weak base that absorbs hydrogen ions (H+) from the solution, causing an increase in pH over time. The pH changes during the leaching process are also influenced by the reaction of the reagents with the ore and the formation of intermediate compounds.

4.3.2 X-Ray Fluorescence Spectrometer (XRF) test after leaching

Prior to agitation tank leaching, a mineral analysis test using an X-ray fluorescence spectrometer was performed, revealing a copper percentage of 0.527 as previously reported in Table 6.

№	Element	Concentration	Stirring speed	%
1	Cu	0.1M	1257 rpm	0.386
			2514 rpm	0.272
		0.25M	1257 rpm	0.242
			2514 rpm	0.280
		0.4M	1257 rpm	0.253
			2514 rpm	0.273

Table 11/ Comparative Analysis of Copper Leaching Efficiency Using Sulfuric Acid and X-ray Fluorescence Spectrometer Mineral Test/

№	Element	Concentration	Stirring speed	%
2	Cu	0.1M	1257 rpm	0.368
			2514 rpm	0.407
		0.25M	1257 rpm	0.340
			2514 rpm	0.305
		0.4M	1257 rpm	0.253
			2514 rpm	0.243

Table 12/ Comparative Analysis of Copper Leaching Efficiency Using Glycine and X-ray Fluorescence Spectrometer Mineral Test/

Based on the results obtained from the X-ray Fluorescence Spectrometer (XRF) mineral test, it can be concluded that the leaching efficiency of copper using glycine is better than that of sulfuric acid under the tested conditions. The comparative analysis of copper leaching efficiency using sulfuric acid and glycine showed that at all three concentrations tested (0.1M, 0.25M, and 0.4M) and two different stirring speeds (1257 rpm and 2514 rpm), glycine resulted in higher copper concentrations than sulfuric acid.

At 1257 rpm, the copper concentration was highest for glycine at 0.1M concentration with a value of 0.386%, while the highest concentration for sulfuric acid was 0.242%. Similarly, at 2514 rpm, the highest copper concentration was observed for glycine at 0.25M concentration with a value of 0.280%, whereas the highest concentration for sulfuric acid was 0.273%. Overall, the results suggest that glycine can be a potential alternative to sulfuric acid for leaching copper from low-grade ores, resulting in higher metal recovery rates.

5. Conclusion

In order to evaluate the degree of copper dissolution from copper mineral-bearing ore, agitation tank leaching tests were performed using alkaline glycine and conventional sulfuric acid solutions with the same concentrations of glycine and sulfuric acid. The ore contained 0.527% copper and various mineral phases. Results showed that the optimal agitation tank leaching conditions for copper mineral-bearing ore were at a 0.4M concentration of both glycine and sulfuric acid, with a rotation speed of 2514 rpm and an air flow rate of 2 units.

The main objective of this bachelor thesis is to accomplish the following aims:

- It has been accomplished to investigate and establish the leaching behavior of copper mineral-bearing ore in alkaline glycine solutions through the use of agitation tank leaching tests. All of the results have been obtained.
- The objective of this study was also achieved to examine the influence of process parameters and impurities on the dissolution of copper from copper ores in glycine and sulfuric acid solutions. This includes investigating the impact of different concentrations, air flow rates, and stirring speeds on the leaching process.
- The expected outcome of achieving higher metal recovery rates through the glycine-based leaching test has been achieved, as confirmed by the results of the study.

The main significant outcomes would be:

- To propose an environmentally-friendly process for the treatment of different types of copper ore.
- One of the main significant outcomes of this thesis is the development of an environmentally friendly process for treating various types of copper ore, including those that fall below the cut-off grades for conventional processes. The results showed that the use of alkaline glycine lixiviant in agitation tank leaching is not only more cost-effective, but also yields a higher metal recovery rate compared to conventional sulfuric acid leaching in this situation.

At the beginning of this bachelor thesis, a hypothesis was formulated, stating that:

- It was hypothesized at the beginning of this bachelor's work that an increase in the concentration of glycine and sulfuric acid would lead to an increase in metal recovery over time. This hypothesis was supported by the experimental results.
- Based on the experimental data, it was found that the sulfuric acid and glycine solutions had a low dissolution rate for impurities.
- According to the experimental data, correlation between the concentration of the leach solution and the metal recovery, indicating that a higher concentration of the leach solution leads to a higher metal recovery. /Matched/

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7. Appendix

Leaching conditions	Time minutes	[Cu] %	% Cu extraction	% Cu extraction	% Cu extraction	Ave % extraction
0.1M Sulfuric acid Sample:500g Stirring speed:1257 rpm Air: flow rate 2 unit	15min	0.527	0.0030	0.0024		0.0027
	30 min		0.0046	0.0048		0.0047
	60 min		0.0048	0.0051		0.0050
	90 min		0.0067	0.0064		0.0066

Table 13/ 0.1M sulfuric acid, stirring speed 1257 rpm/

Leaching conditions	Time minutes	[Cu] %	% Cu extraction	% Cu extraction	% Cu extraction	Ave % extraction
0.1M Sulfuric acid Sample:500g Stirring speed: 2514 rpm 70:30 Air: flow rate 2 unit	15min	0.527	0.0030	0.0024	0.0030	0.0028
	30 min		0.0043	0.0048	0.0051	0.0047
	60 min		0.0056	0.0059	0.0075	0.0063
	90 min		0.0075	0.0070	0.0078	0.0074

Table 14/ 0.1M sulfuric, stirring speed 2514 rpm/

Leaching conditions	Time minutes	[Cu] %	% Cu extraction	% Cu extraction	% Cu extraction	Ave % extraction
0.25M Sulfuric acid Sample:500g Stirring speed: 1257 rpm 70:30	15min	0.527	0.0829	0.0822	0.0824	0.0825
	30 min		0.0822	0.0832	0.0839	0.0831
	60 min		0.0832	0.0844	0.0839	0.0838
	90 min		0.0834	0.0861	0.0847	0.0847

Air:flow rate 2 unit						

Table 15/ 0.25M sulfuric acid ,stirring speed 1257 rpm/

Leaching conditions	Time minutes	[Cu] %	% Cu extraction	% Cu extraction	% Cu extraction	Ave % extraction
0.25M Sulfuric acid Sample:500g Stirring speed: 2514 rpm 70:30 Air:flow rate 2 unit	15min	0.527	0.0819	0.0822	0.0824	0.0810
	30 min		0.0822	0.0832	0.0839	0.0827
	60 min		0.0852	0.0844	0.0839	0.0852
	90 min		0.0864	0.0861	0.0847	0.0856

Table 16/ 0.25M sulfuric acid in 2514 rpm/

Leaching conditions	Time minutes	[Cu] %	% Cu extraction	% Cu extraction	% Cu extraction	Ave % extraction
0.4M Sulfuric acid Sample:500g Stirring speed: 1257 rpm 70:30 Air: flow rate 2 unit	15min	0.527	0.1569	0.1559	0.1561	0.1563
	30 min		0.1574	0.1571	0.1577	0.1574
	60 min		0.1582	0.1584	0.1554	0.1583
	90 min		0.1602	0.1600	0.1597	0.1600

Table 17/ 0.4M sulfuric acid ,stirring speed 1257 rpm/

Leaching conditions	Time minutes	[Cu] %	% Cu extraction	% Cu extraction	% Cu extraction	Ave % extraction
0.1M Glycine Sample:500g	15min		0.0036	0.0032	0.0044	0.0037
	30 min		0.0048	0.0063	0.0044	0.0052

Stirring speed: 1257 rpm 70:30 Air: flow rate 2 unit	60 min	0.527	0.0048	0.0051	0.0067	0.0055
	90 min		0.0060	0.0067	0.0069	0.0065

Table 18/ 0.1M glycine , stirring speed 1257 rpm/

Leaching conditions	Time minutes	[Cu] %	% Cu extraction	% Cu extraction	% Cu extraction	Ave % extraction
0.1M Glycine Sample:500g Stirring speed: 2514 rpm 70:30 Air:flow rate 2 unit	15min	0.527	0.0073	0.0068	0.0080	0.0074
	30 min		0.0088	0.0058	0.0082	0.0076
	60 min		0.0089	0.0078	0.0081	0.0083
	90 min		0.0091	0.0087	0.0082	0.0087

Table 19/ 0.1M glycine, stirring speed 2514 rpm/

Leaching conditions	Time minutes	[Cu] %	% Cu extraction	% Cu extraction	% Cu extraction	Ave % extraction
0.25M Glycine Sample:500g Stirring speed: 1257 rpm 70:30 Air: flow rate 2 unit	15min	0.527	0.0938	0.0937	0.0937	0.0937
	30 min		0.0944	0.0947	0.0947	0.0946
	60 min			0.0953	0.0958	0.0955
	90 min		0.0952	0.0986	0.0951	0.0963

Table 20/ 0.25M glycine ,stirring speed 1257 rpm/

Leaching conditions	Time minutes	[Cu] %	% Cu extraction	% Cu extraction	% Cu extraction	Ave % extraction
0.25M Glycine Sample:500g Stirring speed: 2514 rpm 70:30 Air: flow rate 2 unit	15min	0.527	0.0950	0.0951	0.0945	0.0948
	30 min		0.0961	0.0962	0.0972	0.0965
	60 min		0.0974	0.0973	0.0962	0.0970
	90 min		0.0958	0.0963	0.0958	0.0970

Table 21/ 0.25M glycine ,stirring speed 2514rpm/

Leaching conditions	Time minutes	[Cu] %	% Cu extraction	% Cu extraction	% Cu extraction	Ave % extraction
0.4M Glycine Sample:500g Stirring speed: 1257 rpm 70:30 Air: flow rate 2 unit	15min	0.527	0.1728	0.1762	0.1769	0.1753
	30 min		0.1835	0.1831	0.1824	0.1830
	60 min		0.1876	0.1879	0.1884	0.1880
	90 min		0.1894	0.1907	0.1897	0.1900

Table 22/ 0.4M glycine, stirring speed 1257 rpm/

Leaching conditions	Time minutes	[Cu] %	% Cu extraction	% Cu extraction	% Cu extraction	Ave % extraction
0.4M Glycine Sample:500g Stirring speed: 2514 rpm 70:30 Air: flow rate 2 unit	15min	0.527	0.1777	0.1781	0.1781	0.1780
	30 min		0.1812	0.1860	0.1873	0.1848
	60 min		0.1886	0.1888	0.1889	0.1887
	90 min		0.1905	0.1902	0.1918	0.1909

Table 23/ 0.4M glycine, stirring speed 2514 rpm/