

Advances in Copper Extraction: Sustainable Approaches and Bioleaching Techniques

ABSTRACT

The environmental impacts of mining and mineral processing, particularly in developing countries, have been increasingly significant. Mining activities, especially in open-pit mines and the extraction of copper from sulfide ores, generate pollution and acid leakage that harm ecosystems. Given the abundant presence of copper in nature, particularly in sulfide minerals, developing environmentally friendly extraction methods is paramount. This study evaluates modern and sustainable methods for copper extraction from the Aynak copper mine, one of the largest copper mines in Afghanistan. Specifically, it compares and assesses bioleaching and hydrometallurgical methods as environmentally friendly alternatives to traditional pyrometallurgical (smelting) processes in copper extraction. Compared to pyrometallurgical methods, the study investigates the environmental impacts and economic efficiency of bioleaching and hydrometallurgical methods. The results indicate that biotechnological methods, such as bioleaching, significantly reduce environmental impacts, improve production efficiency, and lower operational costs. In contrast, pyrometallurgical methods are associated with higher environmental and economic costs. Given the advantages of biotechnological methods, it is recommended that these methods be adopted as sustainable alternatives for copper extraction from low-grade ores at the Aynak copper mine, especially from sulfide ores, to promote environmentally and economically sustainable development in the sector.

Keywords: Copper extraction; Aynak ore; bioleaching; environmental pollution; hydrometallurgy; pyrometallurgy.

1. INTRODUCTION

Copper is one of the most widely used and beneficial metallic elements humans have utilized for centuries. While a substantial portion of economically significant copper deposits occurs in sulfide minerals (e.g., chalcopyrite, bornite), copper is also commonly found in oxide forms (such as malachite and azurite) and occasionally as native copper, with sulfide-based ores remaining predominant in most commercial mining operations (MDPI, 2025). Copper extraction from sulfide-enriched minerals, which include copper sulfide and iron sulfide, is carried out through thermal methods (smelting or pyrometallurgy). In contrast, extraction from acidic ores is done through hydrometallurgy (leaching). Currently, 80% of the world's copper production is achieved through thermal methods, and 20% through non-thermal methods (leaching) (ProQuest, 2025). The annual output of sulfur dioxide during the thermal copper extraction process, and its role in environmental pollution, highlights the urgent need for

environmentally friendly methods (Sombhatla et al., 2016). Hydrometallurgy as an alternative to smelting has been studied for a long time, and success has been achieved in this field (Superfund, 2025). Copper extraction through either pyrometallurgical or hydrometallurgical methods, or combined processes, has its own specific characteristics (Montanuniversität Leoben, 2025). However, none of these developed processes have been completely satisfactory, and therefore, new methods and technologies are still being invented in this area. The use of new technologies and techniques such as bioleaching and bio-oxidation offers an effective way for extracting copper from low-grade ores, gold, and other metal resources, which, in addition to simplifying operations, reduces operational costs and causes fewer environmental impacts.

The direct dissolution of copper sulfide minerals, especially chalcopyrite, through acidophilic bacterial oxidation is a cornerstone of bioleaching. This process facilitates the

production of sulfuric acid directly during the bacterial oxidation of sulfide minerals, eliminating the need for sulfur dioxide (SO₂), which is a byproduct of pyrometallurgical processes. The sulfuric acid produced can be utilized in the manufacture of chemical fertilizers, highlighting an added advantage of bioleaching. Together with hydro copper methods, these techniques provide significant environmental and economic benefits over traditional copper extraction methods, including reduced energy consumption, minimized greenhouse gas emissions, and enhanced sustainability."

1. How to produce copper concentrate

The ore extracted from the mine is crushed and ground into fine particles to produce copper concentrate. The fine particles are mixed with water and chemicals in the beneficiation plant and then fed into flotation cells. Air is blown into the cells, creating foam that carries the copper compounds to the surface of the cell. As a result, a concentrate with a grade of over 20% copper is obtained.

2. Copper extraction methods

Copper extraction by thermal method: In the thermal method, the dried sulfide concentrate is smelted in a furnace. During this process, a matte layer, consisting of iron and copper sulfides, forms beneath the slag layer. The temperature of the furnace typically ranges between 1200°C and 1300°C; however, this range can vary depending on the type of furnace and smelting process employed. For instance, in flash smelting, the temperature may be slightly lower due to its efficient heat utilization and advanced energy recovery systems. Typically, the copper content in the matte is more than 30%. If the copper present in the slag is significant, it is recovered using an electric furnace; otherwise, it is discarded. The molten copper matte is transferred to a converter, where impurities such as iron and sulfur are removed through air blasting in two stages, and blister copper is produced. (1). In the first stage of air blasting, iron is removed by adding silica. In thermal methods, the sulfur content in the concentrate, which can vary significantly depending on the mineral composition, is often present in amounts that may be approximately twice the amount of copper. During the smelting process, sulfur is converted into sulfur dioxide (SO₂). Therefore, a significant amount of SO₂ is released into the atmosphere annually. To prevent environmental pollution, it is necessary to find a way to prevent

its dispersion into the air. For example, SO₂ can be converted into sulfuric acid, which can then be used to produce chemical fertilizers. Blister copper, with a purity ranging from 96% to 99%, undergoes sulfur and oxygen removal in two stages using air and natural gas in refining furnaces. The exact purity of blister copper may vary depending on the smelting process. After the refining process, the copper is cast into anodes for electrolytic refining, where it is further purified to produce cathode copper with a purity of 99.99%. The refined copper is then sold in the form of cathode sheets or, after remelting, as slabs, billets, or wires (ScienceDirect, 2025). Therefore, it can be briefly stated that the production of a large volume of SO₂ gas and the necessity to direct this gas for sulfuric acid production, resulting in increased energy requirements for this process, higher costs, and time consumption for copper extraction, are limitations of copper extraction using this method.

Copper extraction by hydrometallurgical method: Copper extraction from oxidized ores through the hydrometallurgical method is also possible. In this process, the oxidized tailings produced in copper mines and copper oxide minerals are leached with sulfuric acid. The copper-rich solution is processed using solvent extraction. The extracted copper is then further treated through electrowinning to produce copper cathodes. This method decomposes the copper concentrate and dissolves in reactors with agitation under oxidizing conditions. However, Chalcopyrite, the dominant copper mineral, does not dissolve easily in sulfuric acid. Its dissolution typically requires oxidative conditions, such as the presence of ferric ions or bacterial bioleaching, rather than alkaline conditions. High-temperature, high-pressure autoclaves are also commonly used to facilitate this process. This requirement is considered a limitation of this method (ACM, 2025).

Hydro copper method: The principle of this method is based on hydrometallurgy, with the distinction that leaching is carried out using chloride solutions. Laboratory studies have demonstrated the dissolution of chalcopyrite below the boiling point of water using divalent copper ions (oxidant). Another advantage of chloride solutions is the stability of monovalent copper and elemental sulfur (S), which are obtained through the decomposition and dissolution of the sulfide mineral (chalcopyrite). In sulfuric acid leaching, more energy is saved, as in this process, copper and sulfur are oxidized

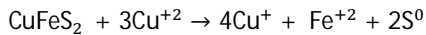
to much higher degrees, with copper reaching a valency of 2 and sulfur reaching a valency of 6 (ScienceDirect, 2025).

The Hydro Copper process consists of three main stages:

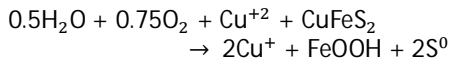
1. Leaching of copper concentrate (leaching, solution purification, and precipitation of Cu_2O).
2. Copper production (reduction of Cu_2O , smelting, and casting).
3. Chemical production (alkaline electrolysis and chlorine production).

Leaching of copper concentrate:

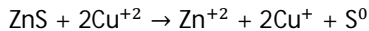
Leaching: Copper concentrate (particularly chalcopyrite) is leached using divalent copper in a chloride medium. The leaching process is carried out under normal pressure in three stages, with divalent copper (copper chloride) facilitating the dissolution of copper and other sulfides (ProQuest, 2025):



Ferrous iron is oxidized to the ferric state in air and precipitates as goethite or hematite.



Other sulfides present in the concentrate are also decomposed, for example:

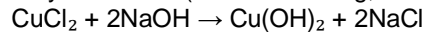


In this method, the concentrate is leached in a countercurrent solution flow under normal pressure at temperatures between 80°C and 100°C, using tanks and agitated thickeners. In each leaching stage, thickeners are used to separate the liquid and solid phases. The solution beneath the third-stage thickener is the final leach residue, which is filtered and washed in a vacuum belt filter. The filter cake is initially washed with water to remove soluble impurities, followed by a wash with a sodium chloride solution to address specific processing needs, and then filtered again. The filter cake is placed in water to minimize its chloride content before being discarded. The leaching time for the concentrate is 10 to 20 hours, with a dissolution efficiency of 98%. A major portion of the sulfur is obtained in its pure form, although a small amount is oxidized and converted to sulfite. The leaching solution contains 60 to 80 grams per

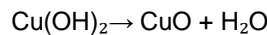
liter of monovalent copper (cuprous) and 10 grams per liter of divalent copper (cupric). By introducing air into the reactors, the pH is indirectly controlled within the range of 1.5 to 2.5 due to oxidation reactions and the dissolution of solids, without the use of acids or bases. The leaching process is controlled by pH and oxidation-reduction equilibrium. In the first leaching stage, cupric ions are reduced as much as possible with fresh concentrate, with minimal or no air used. In the second stage, the amount of oxidant air and the leaching rate reach their highest levels. If the oxidant air flow rate is too high, it increases the pH, causing copper to precipitate as copper hydroxy chloride, which must be avoided. In the third stage of leaching, a high oxidation-reduction potential is maintained.

Solution purification: For copper oxide to precipitate, the solution must have a high level of purity; therefore, solution purification is of great importance. This section includes four stages: removal of divalent copper, precipitation of silver and zinc, lead, and others. The solution purification is carried out using ion exchange, which is performed in sequence.

Copper oxide precipitation: The copper present in the solution precipitates as copper oxide by using a sodium hydroxide solution (obtained from the alkaline electrolysis-chlorine section). Copper oxide precipitates in the second reactor in the form of crystals with an average size of 10-20 microns. After precipitation, the copper oxide is filtered with a vacuum belt filter. The filter cake on the belt is washed with water, and the aqueous NaCl solution obtained from the filter is returned to the alkaline-chlorine electrolysis section (RSC Publishing, 2025).

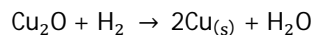


On heating, the copper hydroxide can decompose:



Copper production:

Reduction of copper oxide: The wet copper oxide is transferred from the filter to the corresponding tank for feeding into the rotary furnace, where it is continuously charged using the furnace feeding system. In the presence of a hydrogen-nitrogen flow at a temperature of 400-500°C, the copper oxide is reduced to metallic copper powder.

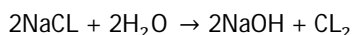


Melting of copper powder and casting:

Copper powder is melted in an induction furnace, and the molten copper undergoes deoxidation. The surface of the molten metal is covered and protected by a layer of graphite powder. A specialized system directs the copper powder beneath this layer for melting (Zhao et al., 2020). The obtained copper quality meets the LME Grade 1 standard and is suitable for casting into desired shapes, with the possibility of producing wire through the casting unit.

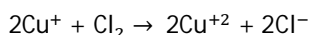
Chemical Production: In the alkaline electrolysis-chlorine section, chemicals enter and exit in a cycle. Using the NaCl solution, which is introduced from the copper oxide precipitation stage, the required alkaline and chloride materials are produced.

Alkaline Electrolysis – Chlorine: This reaction occurs due to the sodium chloride solution:



The solution used for electrolysis must have very few impurities, especially magnesium. Therefore, an ion exchange method is employed in the solution purification stage. The produced sodium hydroxide is sent to the copper oxide precipitation section. Chlorine gas is used for the oxidation of divalent copper ions (cupric), and hydrogen is used for the reduction of copper oxide.

Oxidation of copper solution: Half of the leaching solution of the concentrate enters the oxidation reactor, where, using chlorine gas, cuprous copper is converted into cupric copper.



This reaction takes place in two reactors with very fast agitation, and the solution is returned to the leaching section.

Some of the advantages of using the hydro copper method include:

- The unit is integrated and highly automated;
- Environmental and safety considerations are observed;
- Sulfur is in its pure form (S), and no SO₂ gas is released;
- Any type of copper concentrate is acceptable;
- Precious metals, especially gold, can be recovered and extracted.

Use of the Bioleaching Method:

General principles of copper bioleaching: The bioleaching method is a modern, economical, and environmentally friendly technique for extracting copper, especially from low-grade copper ores. Over the past two decades, its application has significantly increased. Numerous studies have been conducted on combining the bioleaching and bio-oxidation processes for the extraction of both copper and gold concentrates, though it has not yet reached practical application (MDPI, 2025). The principle of this method is similar to leaching, but the major difference is that direct dissolution of copper sulfide ores, especially chalcopyrite, with sulfuric acid is not possible. Therefore, in the bioleaching method, mesophilic bacteria such as *Acidithiobacillus ferrooxidans* are used in the leaching phase to enable the dissolution of chalcopyrite. For high-temperature applications, thermophilic species like *Sulfobacillus* or *Acidianus brierleyi* are more commonly employed (UPC, 2025). Afterward, copper is extracted using solvent extraction and electrowinning, similar to the conventional leaching method, to produce cathode copper. To achieve this, the extracted copper ore is crushed to the desired size and mixed with sulfuric acid in agglomeration units to facilitate the agglomeration of fine particles with coarse particles for bacterial action. To reduce moisture levels for proper agglomeration, water or raffinate (a solution obtained from the recycling of electrowinning solution) is added. If the ore is not highly acidic, the acid required for mineral preparation can be supplied from the raffinate solution. Raffinate usually contains a small number of bacteria that oxidize copper. The bacteria are initially applied onto the heap of ore through pipes to convert the sulfide ore into oxide form. The agglomerated and prepared ore is sent to an acid-leaching area, where it is placed on a heap of 10-6 meters high on land that has been flattened or on top of previously acid-leached ore. The air required for the bacterial operation is supplied through plastic pipes with specialized air holes placed on the pad, and the air needed for ventilation below the ore is provided by pressure blowers. A specific amount of bacterial solution is applied onto the pads, where the bacteria convert the sulfide ore into oxide ore, and the ore dissolves in acid. The enriched solution collects at the bottom of the heap and is sometimes returned to the top of the heap for further processing or directly sent to the solution separation stage for copper recovery if the desired copper content is reached. The raffinate

solution is returned to the acid-leached piles for a second round. The acid leaching time varies for different operations, but ideally, it takes about 200 days for secondary copper ores (Oxford Academic, 2025). The copper recovery and extraction rate in this method is approximately 75-85%.

The optimal temperature, sufficient nutrients for bacterial feeding, adequate oxygen supply, proper ore density, and settling time are key factors for achieving optimal results in the bioleaching process. Studies by Sadowski (2002) on the bioleaching of copper and gold concentrates showed that the process is more effective in the presence of iron ions. The conversion of Fe⁺³ to Fe⁺² indicates the level of bacterial activity, and the presence of various types of sulfides, such as pyrite (at 3%), during the leaching process acts as a catalytic agent in the solution, increasing Fe⁺³ ions. According to these results, copper recovery of up to 86% is achieved after 13 days with the presence of Fe ions and a small amount of pyrite (Chen et al., 2022).

Different methods of copper bioleaching:

Heap Bioleaching: This model, on a large scale, is particularly useful as an economic method for acid heap leaching of copper tailings or ores. Some of the features of this method include low operational costs and a low (solution separation/electrowinning) ratio (Brar et al., 2021).

Table 1. Analysis of Dust Generated at Different Stages of Copper Processing

Prevention Methods	The environment being polluted	Chemical composition	Pollutant stage	Stage name
Use of Scrubber systems			Dust	Crusher (Jaw - Cone)
Use of cyclones, fabric filters, and feed sprinkling	Air	Manganese	Dust	Mill
		Mercury		
		Antimony		
		Chromium		
		Nickel		
		Arsenic		
		Selenium		
Installation of cyanide-sensitive and display systems in the heap and transportation pathways.	Surface water, groundwater, and surrounding land.	Sulfuric acid	Acid leakage from acid transfer pipes and the liners used in the heap structure.	Magnetic separation (high current for hematite and low current for magnetite).
Installation of ventilation systems on tanks.	Air	H ₂ S	Exhaust gas from tanks	Flotation (Fatty acid: collector, Pine oil: frother, Sodium silicate: activator, Sodium hydroxide: conditioner).
Using centrifuge systems to separate fine organic particles	Surface and groundwater	Base metals, precious metals, and organic materials.	Waste (sludge)	Agglomeration.
Installing appropriate filters at the chimney outlet.	Air	SO ₂	Exhaust gases from the furnace.	Purification.

Table 2. Environmental issues of mineral processing operation stages

Pollution control and reduction methods	Environmental issues	Section Name	Unit name
Installation of ventilation systems	Emission of gaseous vapors (SO₂, HCN) from leaching tanks	Reservoir Leaching	Leaching
Control of leaching tanks based on existing standards	Leakage of leaching solution from the tank body		
Storage and handling of chemicals according to existing standards	Contamination of the workplace or chemical storage due to leakage or spillage of the leaching solution		
Transfer of wastewater to the tailings dam	Wastewater production (uncharged solution)	Solvent Extraction -	
Recycling of Used Resins	Used Resins	Electrowinning	
Installation of display systems and sensors for leach solution leakage in heap structure, the proper groundwork for the heap	Infiltration of leach solution into the underlying soil layers and contamination of the area's water resources	Heap Leaching	
Moistening the area during heap construction	Dust emission during heap construction operations		
Control of heap facilities at specified times	Leakage of leachate transfer pipes to the heap and soil contamination		
	Destruction of the area's structure due to heap construction		
	Release of used pipes and liners after the heap's life cycle in the area		
Planting suitable vegetation cover on the heap	The production of a large volume of tailings after the heap's life cycle ends		

Thin layer bioleaching: This method is used exclusively for oxidized ores. Thin layer bioleaching involves the crushing and bioleaching of secondary copper sulfide ores in small heaps (Brar et al., 2021).

Reservoir bioleaching: The first copper bioleaching and its concentrate using reservoir reactors were aimed at achieving faster kinetics. This method, due to its lower recovery from chalcopyrite and its cost-effectiveness compared to continuous smelting, has only been used at a laboratory scale. Bioleaching of chalcopyrite concentrate in the presence of cationic ions such as silver leads to faster kinetics in the experiments and higher copper recovery in laboratory details (ScienceDirect, 2025).

2. DISCUSSION AND CONCLUSION

The mineral processing industry is considered a complementary sector in mining activities. The primary function of this sector is to convert the extracted ore into a concentrate suitable for use in smelting plants and the production of ingots. Generally, the beneficiation process includes stages such as crushing (rock breaking – grinding), classification (screening), gravity separation, magnetic separation, electrostatic separation, filtration, flotation, and leaching. Each of these stages, depending on the type and scale of the operation, utilizes different equipment and operates at varying capacities. The processes often consist of three main branches: input feed, concentrate, and tailings. Furthermore, each stage of the operation has its specific environmental impacts, which typically include water pollution, air pollution, and, in some cases, noise generation. Air pollution occurs during various stages of the comminution process, including crushing and grinding, while water pollution is more commonly observed in the concentration stages. One of the major sources of water pollution is the chemical reagents used during processing operations, particularly in flotation and leaching processes.

In addition to the environmental hazards that can arise during the processing of copper ore, the risks associated with the tailings produced from mineral extraction or the waste materials generated by processing plants, which are also significant challenges in mining, should not be overlooked. The accumulation of these materials in the environment leads to the occupation of large areas, and over time, exposure to air causes subsequent consequences. Therefore, utilizing environmentally friendly biotechnology,

such as bioleaching, along with the other solutions outlined in Tables 1 and 2 for processing the Aynak copper mine, which has been contracted and is about to begin its operational phase, will not only result in energy and economic savings but also prevent adverse environmental and economic impacts in the later stages of production.

In Tables 1 and 2, the environmental impacts at different stages of copper processing are examined, along with solutions to prevent them.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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