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Review article on the technology of leaching of substandard copper concentrates: methods and trends

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ABSTRACT

Recently, due to the depletion of rich copper concentrates, poor, refractory concentrates are increasingly used in copper production. Hydrometallurgical methods are attractive for processing this raw material. This review analyzes modern hydrometallurgical methods for extracting copper from low-grade concentrates. Research focuses on innovative approaches to increase dissolution rates and profitability of leaching refractory copper sulfide minerals. Solving these problems will optimize Cu extraction and expand hydrometallurgy for various ores, improving efficiency and environmental sustainability. Current studies include atmospheric leaching, bioleaching with bacterial mixtures, and autoclave leaching, with optimization of conditions, reagents, and additives to destroy passivation layers and achieve high extraction from chalcopyrite. Hybrid leaching methods are also being developed, combining advantages of different approaches. Each method has advantages and drawbacks, such as passivation layer formation and by-product utilization (sulfuric acid, sulfur, nitrates, iron, chlorine). Overcoming these difficulties remains a key research direction for effective hydrometallurgy. Advances in this field may offer a competitive alternative to traditional pyrometallurgical processing of low-grade copper concentrates.

Récemment, en raison de l'épuisement des concentrés riches en cuivre, on a utilisé de plus en plus de concentrés de cuivre pauvres et réfractaires, dans la production de cuivre. Les méthodes de traitement par hydrométallurgie sont attrayantes pour traiter ce type de matière première. Cette synthèse analyse l'état actuel des méthodes par hydrométallurgie d'extraction du cuivre à partir de concentrés de cuivre de faible qualité. Une partie importante de la recherche est centrée sur le développement d'approches et de technologies innovantes visant à augmenter le taux de dissolution et à améliorer la rentabilité du procédé de lixiviation du cuivre à partir de minéraux sulfurés de cuivre réfractaires. Résoudre ces problèmes permettra à l'industrie d'optimiser l'extraction du cuivre (Cu) à partir de matières premières de faible qualité et d'étendre l'utilisation des méthodes de traitement par hydrométallurgie à des types variés de minerais, ce qui améliorera à long terme l'efficacité globale et la durabilité environnementale des procédés technologiques. Les études modernes en hydrométallurgie comprennent principalement la lixiviation atmosphérique, la biolixiviation utilisant des mélanges bactériens et la lixiviation en autoclave des concentrés de cuivre, avec optimisation des conditions de lixiviation, sélection de réactifs et d'additifs qui permettent la destruction des couches de passivation et une extraction élevée du cuivre à partir de la chalcopyrite. De plus, des méthodes de lixiviation hybrides sont activement développées, combinant les avantages d'approches technologiques variées. Chaque méthode possède des avantages et des inconvénients, y compris la formation d'une couche de passivation à la surface des minéraux et le besoin d'utiliser des sous-produits tels que l'acide sulfurique, le soufre, les nitrates, le fer et le chlore. Par conséquent, surmonter ces difficultés techniques demeure un domaine clé de recherche et développement pour une mise en œuvre efficace des technologies d'hydrométallurgie. Le développement de la recherche dans ce domaine pourrait créer un choix compétitif par rapport aux méthodes de pyrométallurgie traditionnelles de traitement des concentrés de cuivre de qualité inférieure.

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Introduction

Copper, with its atomic number 29, has a long history of human use, dating back at least 10,000 years in Western Asia [1]. Beginning in the Chalcolithic and Bronze Ages, copper played a critical role in the development of human civilisation [2]. Currently, copper is considered one of the 'new strategic metals' in the 'green and digital economy' [3].

According to the US Geological Survey (USGS), global copper production and reserves are showing significant growth, driven by the growing demand for this metal in the modern economy. The growing importance of copper in various industrial sectors is due to its unique physical and chemical properties, including high electrical and thermal conductivity, as well as corrosion resistance. These characteristics contribute to the expansion of the range of innovative applications of copper, including in electric power, transport, mechanical engineering, and medicine [4].

Copper occurs in a variety of natural ore deposits. About 90% of the world's copper reserves are contained in sulphide ores, where the main minerals are covellite (CuS), chalcosite (Cu_2S), chalcopyrite ($CuFeS_2$) and bornite (Cu_5FeS_4). The remaining 10% of copper reserves are represented by oxidised minerals such as malachite ($Cu_2CO_3(OH)_2$), azurite ($Cu_3(CO_3)_2(OH)_2$) and cuprite (Cu_2O) [5]. The copper content in typical copper ores varies from 0.5% for open pits to 1–2% for underground mines [6].

Based on current estimates, global copper reserves, defined as economically recoverable metal content, are projected to be around 870–900 million tons by 2025.

A comparative analysis of world copper reserves in 2025 (Figure 1) demonstrates significant variability in the distribution of resources by country. Thus, the leader in copper reserves is Chile, where the volume of reserves is estimated at 200 million tons, which corresponds to 27-28% of the total world volume. Kazakhstan ranks 12th with reserves of about 30 million tons, and is the leader among the CIS countries. In Kazakhstan, there is an intensive introduction of modern hydrometallurgical technologies, which, combined with the high potential for processing tailings and waste in the form of raw materials, creates favourable conditions for the further development of the copper industry.

Traditionally, the main raw material for copper production is sulfide ores, and less commonly, mixed and oxidised ores. Due to the relatively low copper content in the sulfide ores and their multi-component nature, the ores firstly undergo flotation enrichment. This process yields copper and other associated concentrates, depending on the metal impurities present in the ore. While previously, when processing rich ores, the copper content in concentrates reached 18-45%, in recent years, due to the depletion of rich deposits, lean concentrates containing no more than 10% copper are increasingly being produced.

The processing of sulphide copper concentrates is mainly based on successive thermochemical pyrometallurgy processes, including roasting, high-temperature smelting (>1200 °C), and conversion, which results in blister copper.

During oxidative roasting of sulphides, SO_2 is partially removed, and the smelting process promotes maximum removal of sulphur in the form of SO_2, transformation

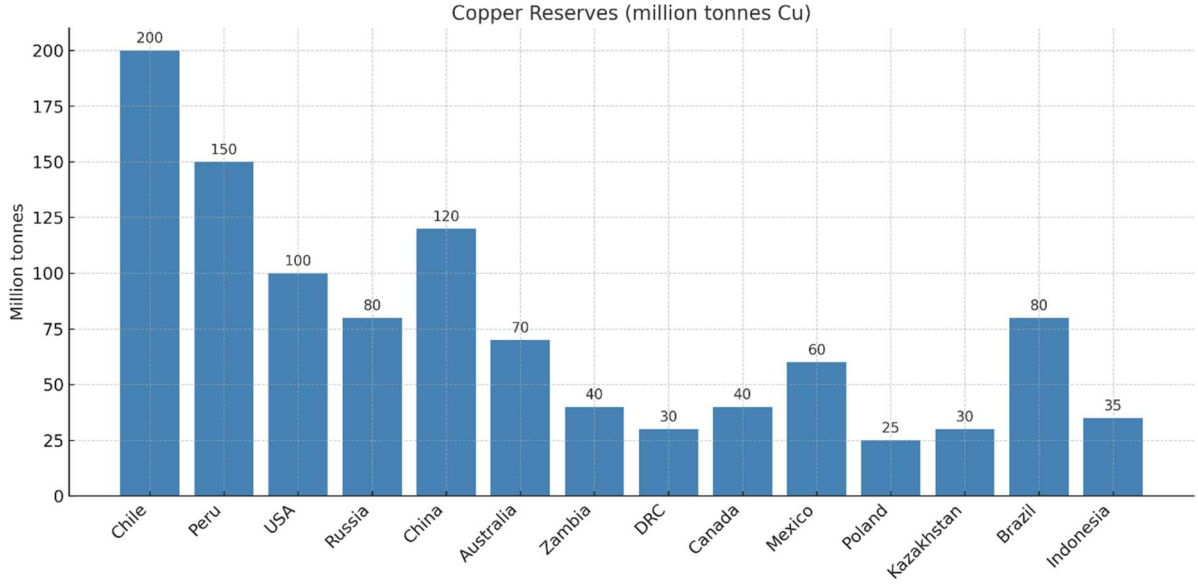


Figure 1. Comparative analysis of world copper reserves in 2025 by country.

of sulphide phases into oxide compounds, and transition of iron into slag. The converter process ensures production of crude metal with a copper content of 95 up to 98%. Subsequent electrolytic refining of blister copper results in the final product – high – grade cathode copper, purity exceeding 99.9% [7].

Despite the high productivity, reaching 2,000 thousand tons of copper per year at large enterprises, this process is characterised by significant energy consumption, amounting to approximately 3–4 GJ per ton of copper, at the smelting and converting stages, requires the use of complex gas cleaning systems to capture SO_2 and has a significant impact on the environment due to emissions of sulfur gases, dust containing heavy metals, the formation of large amounts of slag, water pollution in the processes of refining and cleaning copper, etc. [8, 9].

Currently, modernisation and improvement of existing pyrometallurgical technologies are being carried out, and alternative technologies, such as combined and hydrometallurgical technologies, are proposed for processing poor copper concentrates. The integration of various processes in combined technologies can create new technological risks and require careful optimisation of transition stages. Therefore, hydrometallurgical processing methods are preferable for processing substandard copper concentrates.

Hydrometallurgical methods of processing copper sulphide concentrates have a number of advantages over pyrometallurgical ones:

1. Reduction in energy consumption, since leaching is carried out at temperatures not exceeding 100 °C, which leads to a reduction in energy consumption by 30-40% compared to pyrometallurgical smelting [9], i.e. hydrometallurgical methods have a smaller carbon footprint, which is in line with modern trends in sustainable development.
2. Reduction of emissions and improvement of environmental safety. During leaching, sulfur-containing components pass into solution mainly in the form of sulfates, which allows up to 95% of sulfuric acid to be regenerated for reuse. In contrast, pyrometallurgy generates SO_2 emissions reaching 1.2 tons per ton of copper produced [8].
3. Flexibility in terms of feedstock composition, effectively extracting copper from substandard concentrates and electronic waste (e-waste) with a yield of up to 95%. For comparison, pyrometallurgical technologies require the use of concentrates with a copper content of at least 25% to ensure profitability [8, 10]. The use of modified aldoxime extractants helps to increase the selectivity of copper extraction to a Cu:Fe ratio of 10:1 with an extraction of over 90% in one cycle [10].
4. Low costs in the construction of hydrometallurgical facilities, for example the construction of a hydrometallurgical plant with a capacity of 100 thousand tons of copper per year costs between 200 and 300 million USD [11].
5. Obtaining cathode copper with a purity of over 99.99% with a specific energy consumption of 2.2–2.4 kWh per kg of copper [12].
6. The possibility of developing remote deposits, i.e. solving logistical problems with the installation of compact and less demanding hydrometallurgical installations on infrastructure.

Thus, when processing substandard copper concentrates, hydrometallurgy is characterised by energy consumption that is 30-40% lower compared to pyrometallurgy, ensuring the extraction of up to 95% of copper from complex raw material flows. This method significantly reduces SO_2 emissions _ from a level of approximately 1.2 tons per ton of copper, typical for pyrometallurgy, to virtually zero values when implementing a closed cycle of sulfuric acid use. In addition, the hydrometallurgical approach makes it possible to obtain a final product with a purity of at least 99.99% with a specific energy consumption of about 2.3 kWh per kg of copper [8, 9, 12].

Problem

The growing interest in recent years in hydrometallurgical methods of processing poor substandard concentrates is due to a complex of interrelated technological, economic and environmental factors. These include a significant imbalance between supply and demand for copper, deterioration in the quality of ore raw materials, and the involvement of low – grade oxide and secondary sulfide ores in processing [13–15]. The concentrates being processed are characterised predominantly by a low copper content, not exceeding 10%, which presents significant technological difficulties for pyrometallurgical processes.

The need for efficient processing of low-grade and complex copper ores and concentrates stimulates the development of hydrometallurgical technologies. Given the potential shift of the main sources of copper towards low-grade raw materials, the development of highly efficient technologies for the extraction and processing of this metal is of critical importance [16].

In addition, the intensification of research in the field of copper hydrometallurgy is related to environmental aspects and the possibility of processing mixed and

low-grade ores with a copper content of about 0.4-0.5% [17]. Industrial leaching processes require strict control of atmospheric emissions and the development of more environmentally friendly technologies [18–20]. These factors are becoming key to meeting international commitments such as the Paris Agreement on emission reduction and adaptation to climate change [21].

Basic leaching methods

Currently, various methods are used for leaching copper concentrates, which are conventionally divided as follows:

- Atmospheric leaching [22–29].
- Autoclave leaching [30–33].
- Ammonia leaching [34–37].

The flow chart of copper concentrate leaching methods is shown in Figure 2.

Atmospheric leaching is an important hydrometallurgical process used to extract copper from poor and complex concentrates. This method attracts the attention of researchers and industrial specialists due to its technological simplicity, cost-effectiveness and compliance with modern environmental standards. The process is carried out at atmospheric pressure using acidic (e.g. H_2SO_4) or alkaline leaching solutions and is often accompanied by the introduction of oxidising agents such as Fe^{3+} ions, hydrogen peroxide (H_2O_2), chlorine, pyrolusite MnO_2 and others [38–40].

The mechanism of atmospheric leaching is based on the chemical oxidation of sulfide minerals. Copper sulfides, including chalcopyrite ($CuFeS_2$), undergo

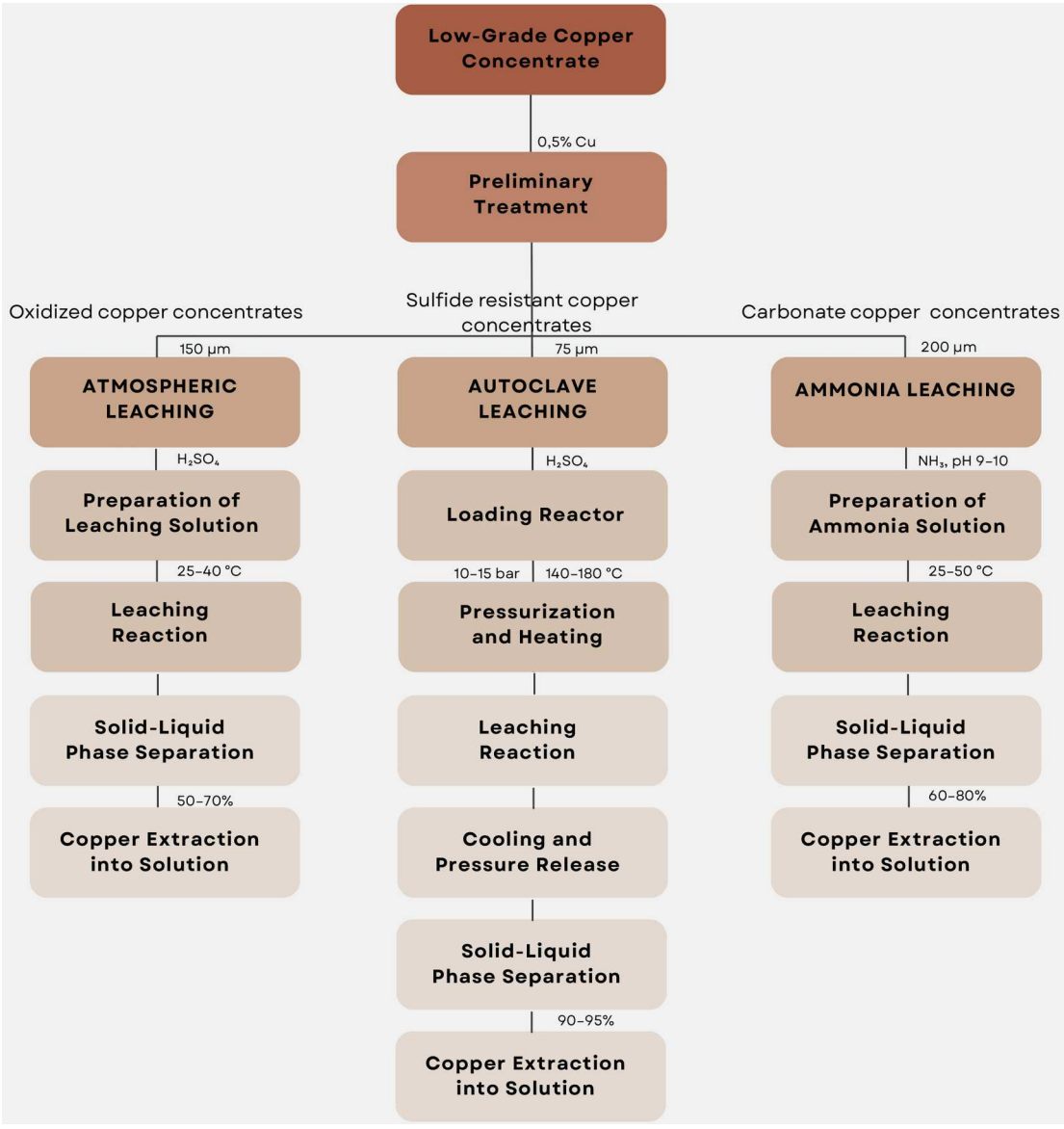


Figure 2. Flow chart of leaching methods.

oxidation in the presence of acids (H_2SO_4) and oxidisers (Fe^{3+}, O_2), when interacting with HNO_3, Cl_2, as described in the following oxidation–reduction reactions [41–45]:

$$CuFeS_2 + 4H^+ + O_2 \rightarrow Cu^{2+} + Fe^{2+} + 2S^0 + 2H_2O$$

$$CuFeS_2 + 4H_2O_2 + 4H^+ \rightarrow Cu^{2+} + Fe^{2+} + 2SO_4^{2-} + 6H_2O$$

$$CuFeS_2 + 8HNO_3 \rightarrow Cu(NO_3)_2 + Fe(NO_3)_2 + 2S^0 + 4H_2O + 4NO_2$$

$$CuFeS_2 + Cl_2 + H_2O \rightarrow Cu^{2+} + Fe^{3+} + SO_4^{2-} + 2Cl^- + 2H^+$$

Atmospheric leaching is the most economical and widely used method for processing concentrates containing some easily leached sulphide ores/concentrates (e.g. chalcocite, covellite). However, its application to refractory chalcopyrite at atmospheric pressure is often time-consuming and may be incomplete due to passivation, leading to the search for more intensive methods (pressure leaching, hybrid processes).

Bioleaching of sulfide minerals is a complex, technologically mature process that is influenced by many factors. Key factors determining copper leaching performance from sulfide ores include the type of microorganisms, pH of the environment, temperature, oxidation–reduction potential, pulp density, particle size, availability of nutrients, oxygen and carbon dioxide, and the presence of toxic elements. All of these factors affect bacterial activity and the rate of mineral dissolution. Bioleaching of copper sulfide ores is based on the oxidation of sulfide minerals by microorganisms and is an environmentally friendly alternative to pyrometallurgical technologies for copper production [46].

Currently, bioleaching accounts for up to 15–20% of global copper production, especially in countries such as China and Chile [46].

Bioleaching of copper sulphide ores, including chalcopyrite ($CuFeS_2$), is carried out using mesophilic bacteria resistant to 45°C and thermophilic bacteria functioning in the range of 45–110°C. Representatives of mesophilic bacteria include, for example, *Acidithiobacillus ferrooxidans*, *Leptospirillum ferrooxidans* and *Acidithiobacillus thiooxidans*. Thermophilic bacteria include members of the order *Sulfolobales* from the genera *Acidianus* (e.g. *A. brierleyi*), *Metallosphaera* (*M. hakonensis*, *M. sedula*, *M. prunae*), *Sulfuracidifex* (*S. metallicus*, *S. tepriarius*), *Sulfolobus* (*S. acidocaldarius*), *Saccharolobus* (*S. solfataricus*) and *Sulfurisphaera* (*S. ohwakuensis*, *S. tokodaii*). The effects of these microorganisms on copper leaching have been studied in detail [47–52].

The mechanism of bioleaching of chalcopyrite involves its oxidation with the formation of polysulfide intermediate products. This process is initiated by chemical interaction with trivalent iron (Fe^{3+}). Under the action of acid, constantly generated by bacteria, the following reactions occur:

$$CuFeS_2 + 2Fe_2(SO_4)_3 \rightarrow CuSO_4 + 5FeSO_4 + S_2$$

$$CuFeS_2 + O_2 + 2H_2SO_4 \rightarrow CuSO_4 + FeSO_4 + 2S^0 + 2H_2O$$

Next comes the biooxidation of iron from Fe^{2+} to Fe^{3+}

$$2FeSO_4 + 1/2O_2 + H_2SO_4 \rightarrow Fe_2(SO_4)_3 + H_2O$$

Bacteria also destroy passivating layers (for example, elemental sulfur S^0).

$$2S^0 + 3O_2 + 2H_2O \rightarrow 2SO_4^{2-} + 4H^+$$

According to reaction 5, a passivating layer is formed as a result of the precipitation of iron-containing complexes.

$$Fe_2(SO_4)_3 + 2H_2SO_4 + 6H_2O + M^+ \leftrightarrow MFe_3(SO_4)_2(OH)6 + 6H^+$$

Recently, researchers have focused their attention on moderately thermophilic bacteria, which demonstrate a number of decisive advantages. These advantages are due primarily to higher growth rates and the ability of microorganisms to function under conditions that destroy refractory minerals. Leaching at elevated temperatures generally results in higher rates of chemical reactions. Research confirms that microorganisms (such as Acidithiobacillus ferrooxidans and Leptospirillum ferrooxidans) significantly accelerate the oxidation of sulfides [53].

At low temperatures (around 35°C), non-stoichiometric intermediate copper sulfides formed on the chalcopyrite surface create a significant diffusion barrier due to their lower reactivity compared to the parent sulfide. In contrast, at elevated temperatures (e.g. 68°C), these intermediate sulfides do not form a diffusion barrier due to their dissolution [54]. Therefore, the use of thermophilic microorganisms for metal extraction and reclamation demonstrates higher efficiency compared to mesophilic ones. However, copper can exhibit toxicity to thermophiles when a certain threshold concentration is exceeded [55].

Although mesophiles have greater tolerance to high metal concentrations than thermophiles, bioleaching of chalcopyrite-containing ores or concentrates using

mesophilic bacteria is characterised by slow dissolution kinetics, resulting in incomplete copper recovery.

Modern biological oxidisers used in atmospheric leaching include:

Optimised indigenous and mixed microbial consortia (including, for example, Acidithiobacillus caldus, A. ferrooxidans and L. ferrooxidans), which demonstrate high efficiency in the regeneration of oxidants and the removal of passivating sulfur layers [56–58].

New strains of bacteria and archaea (such as Ferroplasma spp.), isolated from extremely acidophilic environments and capable of functioning under harsh conditions during the processing of low-grade copper concentrates [56–58].

One of the main limitations for the effective application of biohydrometallurgy to copper ores remains the low leaching rate of chalcopyrite. To overcome this limitation, two-stage leaching processes combining biological and chemical oxidation have been proposed to further enhance metal recovery. These advances, supported by recent experimental data and research, open up prospects for more efficient and environmentally friendly approaches to processing low-grade copper ores.

Despite significant advances, the development of highly efficient chalcopyrite bioleaching technologies for copper recovery remains a challenging scientific and technical task.

Atmospheric leaching is characterised by low capital costs and ease of installation due to operation at atmospheric pressure and ambient temperatures, and demonstrates flexibility in processing a variety of ore types, including low-grade concentrates.

The method is accompanied by a number of limitations, such as low intensity of chemical reactions, which can lead to insufficient metal extraction, the formation of passivating layers on the surface of ore particles, and the dependence of efficiency on external factors, including climatic conditions and temperature regime.

To eliminate the above-mentioned shortcomings, the following approaches are proposed: optimisation of the concentration of acid reagents with the introduction of oxidising additives to activate processes, the use of mechanical methods (agitation, ore crushing) to increase the specific contact area, and the development of modified reagent systems that prevent the formation of passivating barriers.

Practical application of atmospheric leaching technology has been implemented at large deposits, including Morenci Mine (Arizona, USA), Escondida Oxide and Radomiro Tomic (Chile), Cerro Verde (Peru), Lumwana Mine (Zambia) and other mining facilities.

Pressure leaching is a hydrometallurgical process used to extract copper from refractory copper concentrates, including chalcopyrite ($CuFeS_2$). The process is carried out under elevated temperature and pressure conditions using acidic solutions and oxidisers. This method is highly efficient and environmentally safe, surpassing pyrometallurgical technologies in these respects [59–64].

The mechanism of autoclave leaching is based on the oxidation of sulfide minerals by oxygen. For chalcopyrite, the general oxidation reaction is described by the following equation [65, 66]:

$$CuFeS_2 + 4O_2 + 2H_2SO_4 \rightarrow CuSO_4 + FeSO_4 + 2H_2O$$

Intensification of the oxidation process is achieved by increasing the temperature to 150–200°C and the pressure to 1,400–2,100 kPa, leading to acceleration of the reaction kinetics and maximum copper extraction [67].

Autoclave leaching is characterised by high intensity of copper extraction and efficiency in processing ores containing significant volumes of dispersed sulphide phases, due to the use of elevated temperatures and pressures in the reaction environment.

The method is characterised by high capital and energy costs, as well as the need for strict compliance with industrial safety requirements due to the operation of equipment under excess pressure and thermal load.

To minimise these limitations, the following measures are proposed: the use of materials with increased corrosion resistance, optimisation of thermal and mechanical impact modes, and the introduction of automated process parameter control systems, including monitoring of pressure, temperature, and chemical composition of the solution.

Autoclave leaching technology has been implemented at industrial sites such as Bagdad Mine (Arizona, USA), Gedabek Mine (Azerbaijan), Chambishi Cobalt Plant (Zambia), projects of Zijin Mining (China), and the Verde deposit (Peru).

Ammonia leaching is a hydrometallurgical method for extracting copper from low-grade or refractory concentrates, which has found wide application due to its environmental sustainability and high selectivity for copper. This approach demonstrates particular efficiency in processing copper minerals with high carbonate content, where acid leaching results in significant reagent costs and losses of the useful component or causes problems with impurities [68–70].

The mechanism of ammonia leaching is based on the dissolution of copper minerals in ammonia-ammonium carbonate solutions. For oxide minerals such as malachite ($Cu_2(OH)_2CO_3$) and azurite ($Cu_3(OH)_2(CO_3)_2$),

the dissolution process can be described by the following reactions:

$$Cu_2(OH)_2CO_3 + 4NH_3 + H_2O \rightarrow 2[Cu(NH_3)_4]^{2+} + CO_3^{2-} + 4OH^-$$

Copper sulfide minerals such as covellite (CuS) or chalcocite (Cu_2S) require the presence of oxidising agents such as oxygen or hydrogen peroxide:

$$Cu_2S + 4NH_3 + 12O_2 + H_2O \rightarrow 2[Cu(NH_3)_4]^{2+} + S^{2-}$$

The resulting copper ammonia complex $[Cu(NH_3)_4]^{2+}$ has high stability, which ensures efficient copper extraction [71].

Ammonia leaching is characterised by high selectivity of copper extraction, due to the specific interaction of ammonia complexes with target metals, and is carried out under moderate process conditions, which reduces the corrosive aggressiveness of the environment and extends the service life of the equipment.

The method is characterised by relatively low reaction kinetics compared to autoclave processes and is associated with technological difficulties in controlling the volatility of ammonia, which can cause reagent losses, increased costs for its compensation and the risk of environmental pollution from emissions of ammonia vapours.

To improve efficiency and reduce negative impacts, the following measures are proposed: implementation of closed ammonia recirculation cycles with ammonia capture systems, optimisation of the composition and acid–base balance of leaching solutions, and the use of integrated systems for monitoring and cleaning exhaust gases to minimise emissions.

Ammonia leaching technology has been implemented at industrial sites including Tsumeb Smelter (Namibia), Kennecott Utah Copper (USA), Britannia Mine (Canada), Sepon Mine (Laos) and other enterprises specialising in the processing of complex ore matrices.

Comparative indicators of various leaching methods obtained in studies [72, 73] reflect approaches to increasing the efficiency of processes and specific features of each method, reflected in Table 1.

Factors affecting copper recovery from concentrates

The main factors determining the efficiency of copper extraction are the following:

1. Temperature and pressure. In the autoclave method, elevated temperature and pressure intensify the decomposition of sulphide minerals. For atmospheric and ammonia leaching, temperature affects the process kinetics without requiring extreme conditions.
2. Particle size. Reducing the particle size increases the reaction surface area, but leads to an increase in energy costs for grinding and consumption of reagents.
3. Use of oxidising agents. Oxidisers (H_2O_2, O_2, Fe^{3+}, etc.) prevent passivation of mineral surfaces, for example, by elemental sulfur. In the ammonia method, oxidising agents compensate for the low oxidising capacity of ammonia (NH_3).
4. Concentration of reagents. In acid leaching For poor concentrates (atmospheric and autoclave leaching), the critical parameter is the concentration of acids – H_2SO_4, HNO_3, etc. In the ammonia process, pH control and maintaining optimal NH_3 concentration are of key importance.
5. Mineralogical composition of the original concentrates. Atmospheric leaching is most effective for sulphide concentrates containing relatively readily soluble sulphides. The autoclave method demonstrates high efficiency in processing substandard sulphides containing more chalcopyrite. Ammonia leaching provides selectivity to copper in carbonate or alkaline ore matrices.

Analysis of data on copper concentrate processing methods allows for a comprehensive assessment of technical, economic and environmental aspects. A comprehensive comparative analysis based on the results of studies [83–85] is presented in Table 2.

Thus, a comprehensive comparative analysis of the technological, economic and environmental aspects of various leaching methods helps to optimise the choice of the most effective technology. As Table 3 demonstrates, a systematic assessment of key factors enables the identification of potential constraints and ensures balanced decision making that combines operational efficiency with environmental sustainability.

Despite the technological complexity and ambiguity of solutions, the current stage is characterised by the active development of new hydrometallurgical projects for the processing of low-grade copper concentrates using advanced technological approaches. A summary of the current industrial projects with key parameters is presented in Table 4.

Promising developments in copper concentrate leaching technology

Electrochemical reductive leaching (Still Bright), developed by the company of the same name, uses an electrochemical approach to process copper concentrates. The

Table 1. Comparative indicators of the leaching process.

Key parameters	Types of leaching		
	Atmospheric	Autoclave	Ammonia
Temperature	Increasing the temperature improves the reaction kinetics. For example, at a temperature of 40°C, the efficiency of copper extraction from chalcopyrite concentrate was 90.6% in 6 h [74]	Increasing temperature and pressure helps to accelerate chemical reactions. In [75] it was shown that copper extraction from chalcopyrite reaches 95% at a temperature of 200°C and a pressure of 2,100 kPa.	Increasing the temperature helps to accelerate the kinetics of reactions. Experiments [76] showed that when the temperature was increased from 30°C to 60°C, the degree of copper extraction from chalcopyrite increased by 30%
Particle size	Reducing particle size increases the reaction area but can lead to increased reagent consumption and phase separation problems.	Smaller particles provide more surface area for reaction, which increases leaching efficiency. However, excessive grinding can increase energy costs.[77] noted that when the particle size was reduced to 20 μm, the degree of copper extraction increased by 15%	Fine grinding increases the surface area of the minerals, which results in higher copper recovery. However, excessive grinding can lead to increased reagent consumption [78]
Oxidisers	The use of H_2O_2 and Fe^{3+} significantly accelerates the leaching of sulphide minerals, minimising the formation of passive layers. For example, the use of 1% H_2O_2 improved the recovery of copper and nickel from tailings [42]	Oxygen (O_2): The most common oxidising agent, providing efficient oxidation of copper sulfides. Sulfur Dioxide (SO_2): Can be used in combination with oxygen to improve process kinetics. Hydrogen peroxide (H_2O_2): Sometimes used to speed up oxidation reactions.	The presence of oxidising agents such as oxygen or hydrogen peroxide significantly accelerates the dissolution of sulfide minerals. In studies [42] It was shown that the use of hydrogen peroxide in an ammonium carbonate medium increased copper extraction by 25%
Concentration	Higher concentrations of sulfuric acid (up to 2 M) promote the dissolution of copper minerals. Study [79] showed that for concentrates with 15% Cu, the recovery rate reached 78% in 24 h with the addition of 1% H_2O_2	High concentrations of H2SO4 improve copper dissolution but can result in excess iron in solution, complicating subsequent processing [80]	Maintaining pH at 9–11 is important to prevent ammonia hydrolysis and ensure optimal copper recovery. Research [81] showed that at NH_3 concentrations >2 the leaching efficiency increases significantly
Peculiarities	Aeration and mixing Adequate oxygen supply and vigorous mixing maintain suspension and improve mineral dissolution.	Partial Oxygen Pressure For efficient leaching, high oxygen levels must be maintained. Research [3] confirmed that lack of oxygen leads to passivation of minerals, which reduces copper extraction. Leaching duration Increasing the leaching time allows complete dissolution of copper, but may promote the formation of passive layers such as sulfur or jarosite. [78] demonstrated that the optimal time for autoclave leaching of pyrite – copper concentrate is 3 h	Mineralogical composition Ammonia leaching is effective for copper minerals and has little effect on iron, aluminum and other impurities. However, minerals such as chalcopyrite require optimisation of the oxidiser dosage to prevent passivation by sulfur [82]

technology enables the extraction of 40–70% of copper from chalcopyrite, significantly exceeding traditional smelting (15–30%) [101, 102]. It is expected to reduce dependence on energy-intensive smelting and minimise environmental impact by eliminating SO_2 emissions [103, 104].

Galvanox (galvanic atmospheric leaching) *method* developed at the University of British Columbia improves copper recovery from primary sulphide concentrates by controlling galvanic interactions between pyrite and chalcopyrite [105, 106]. Predicted results include >90% copper recovery under atmospheric conditions, reduced acid consumption and oxygen demand, reduced operating costs and reduced environmental impacts.

HydroCopper hydrochloride leaching technology enables direct copper recovery from sulphide concentrates, bypassing the smelting stage [107, 108]. Key expected benefits include closed-loop NaCl regeneration via chlor-alkali electrolysis, minimisation of waste and reagent costs while eliminating acidity issues.

The Fast Oxidative Leaching (FLSmidth) process implements innovative atmospheric leaching at ~80°C to remove passivation layers from sulphide concentrates [109, 110]. The technology enables >98% copper

Table 2. Technical, economic and environmental analysis.

Methods	Cost comparison			Environmental Impact
	Capital expenditures (million dollars)	Operating expenses (million dollars/kg cubic m)	Energy (kWh/kg)	
Atmospheric	10–50	1,5	15	High acid consumption; tailings require neutralisation.
Autoclave	200–500	2,8	45	SO_2 emissions but high energy requirements.
Ammonia	50–150	1,2	25	Minimal use of acids; NH_3 recycling reduces waste.

Table 3. Problems and solutions in leaching of low-grade copper concentrates.

Problem	Data/Figures	Solution	Result
Low dissolution rate of chalcopyrite ($CuFeS_2$)	Leaching time: 7–14 days. Cu yield: < 70% by atmospheric leaching.	Introduction of catalysts (Cl^-, Ag^+) or bacteria (Acidithiobacillus).	The process is accelerated by 30-50%, and Cu extraction increases to 85-90%. [86, 87]
High acid consumption (H_2SO_4)	Acid consumption: 500–800 kg/t ore for sulphide ores.	Use of acid regeneration through oxidation of $Fe^{2+} \rightarrow Fe^{3+}$ by bacteria.	Reduction of H_2SO_4 consumption by 40-60%. [88, 89]
Passivation of mineral surfaces	Formation of a S^0 or jarosite ($KFe_3(SO_4)_2(OH)_6$) layer reduces recovery by 20-30%.	Addition of chlorides (NaCl: 10–50 g/l) to destroy S^0.	Elimination of passivation, increase in Cu extraction up to 85%. [67, 90]
Low bacterial activity	Optimum temperature for mesophiles: 30-40°C. At <25°C the speed drops by 70%.	The use of thermophilic strains (Sulfolobus spp.) for operation at 60-80°C.	Increase in oxidation rate by 2–3 times. [87, 91]
Energy consumption of the process	Autoclave leaching requires 35–50 kWh /t of ore.	Transition to atmospheric bioleaching with aeration (energy consumption: 5–10 kW h /t).	Cost reduction by 70-80%. [88, 92]
Low copper content	Cu concentration in ore: 0.2-0.5%. Economic threshold: ~0.3% for heap leaching.	Optimisation of grinding (<75 μm) and agglomeration of ore.	Increase in Cu extraction by 15-20% even at a content of 0.2%. [13, 93]

Table 4. Summary table of new projects for hydrometallurgical processing of low-grade copper concentrates.

Project	Technology	Content Cu	Extraction (%)
Jetti Resources [94, 95]	Catalytic	0.2–0.4%	85–90
Zijinshan [96]	Chloride	0.3–0.5%	95
Terrafame (Sotkamo) [97]	Bioleaching	0.15%	80
QB2 (Teck) [98]	Hybrid H_2SO_4 + bio	0.45%	70
Florence Copper [99]	Underground leaching	0.33%	85
Rio Tinto Nuton [100]	Bio + nanoparticles	0.5%	90 (target)

recovery in less than 6 h (versus 20–60 h in conventional processes), providing increased productivity, reduced energy consumption, capital and operating costs, and a minimal environmental footprint.

Nitric acid leaching (Kazakhmys Smelting), which is undergoing pilot testing, is based on the NH_4NO_3 +H_2SO_4 system for processing low-grade and refractory concentrates with recovery of up to 80% copper [72, 111, 112]. Subsequent processing of solutions by extraction and electrolysis methods ensures the production of high-purity cathode copper. Increased processing speeds and improved environmental performance are expected.

Conclusion

Leaching of off-grade (substandard) copper concentrates remains an important area of research aimed at improving copper recovery efficiency. Current advances in pressure leaching, bioleaching and hybrid approaches show significant potential, achieving recoveries of up to 90% under conservative conditions. However, large-scale industrial implementation of these technologies requires addressing critical issues including impurity management, preventing sulphur passivation and optimising energy consumption.

Further development of this research area is associated with the integration of advanced technologies, the use of hybrid methods and the rational use of resources. Experimental sites located in different geographic regions contribute to the improvement of technological processes, ensuring an increase in the level of copper extraction, a decrease in production costs and a minimisation of environmental impact. The successful implementation of these developments depends on interdisciplinary cooperation between scientific organisations, industrial enterprises and government agencies.

An analysis of modern leaching methods has led to the identification of their key characteristics and areas of applicability.

Atmospheric leaching of low-grade copper concentrates, although an economically attractive and relatively simple method, has limited effectiveness for refractory sulphide minerals due to slow kinetics and passivation issues, requiring further research and optimisation.

Autoclave leaching demonstrates high efficiency in processing refractory sulphide ores, although it is associated with significant energy costs.

Ammonia leaching is a promising hydrometallurgical process, especially suitable for low-grade and substandard copper concentrates. It becomes an ideal choice when traditional acid leaching is ineffective or problems with undesirable impurities in the raw material arise. For deposits with high carbonate mineral content, ammonia leaching provides an optimal balance between economic profitability and environmental safety.

Much of the current research is focused on overcoming the inertness of chalcopyrite and optimising process parameters to reduce copper production costs. Leading companies in this area are Jetti Resources (USA) and Zijin Mining (China), while Terrafame stands out among European companies, and Kamoa-Kakula in the African region.

The prospects for the development of leaching of substandard copper concentrates are determined by the

integration of hybrid technological solutions. Such approaches as a combination of autoclave and ammonia methods, the use of artificial intelligence algorithms for automation and optimisation of processes, as well as the introduction of extraction reagent recirculation systems are considered promising. Such synergy can ensure the creation of hybrid systems with minimal waste generation. It is predicted that by the end of the current decade, these approaches will increase the profitability of processing low-grade concentrates by 15-20%, opening up opportunities for the economically viable development of previously unprofitable deposits. The implementation of these solutions will increase the resource efficiency of copper production, reduce costs and reduce the negative anthropogenic impact on the environment.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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