



# Materials-driven technologies and intelligent control for mineral processing wastewater recovery

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## ARTICLE INFO

### Keywords:

Mineral processing wastewater  
Wastewater treatment technology  
Resource recovery

## ABSTRACT

Mineral processing wastewater poses severe environmental risks due to its complex composition (high suspended solids, residual reagents, heavy metals), making its treatment critical for sustainable mining. This review systematically summarizes mineral processing wastewater treatment technologies, including conventional methods and emerging approaches. Conventional physical-chemical methods are widely used but suffer from sludge production and limited resource recovery. Advanced oxidation processes (e.g., plasma oxidation, photo-Fenton) efficiently degrade refractory organics and novel adsorbents (MOFs, selective resins) enable targeted heavy metal recovery and deep purification. Artificial intelligence and digital twin further promote intelligent process control. Future directions focus on integrating multi-technologies into “classification treatment-quality-based reuse” systems to achieve comprehensive recovery of water, salts, and valuable metals, advancing mining towards a circular economy and near-zero discharge.

## 1. Introduction

Mineral processing is a crucial step in the exploitation and utilization of mineral resources. It involves separating valuable minerals from gangue via physical or chemical methods to obtain high-grade concentrates [1,2]. However, this process generates large volumes of wastewater with complex compositions and high pollution loads, primarily originating from concentrate and tailings dewatering, equipment cleaning, and site spillage or leakage [3–5]. Statistics indicate that processing one ton of ore typically consumes 4–6 tons of water, most of which ultimately becomes wastewater [6]. This wastewater is typically characterized by high suspended solids content, diverse residual chemicals, and elevated heavy metal ion concentrations. Direct discharge without treatment can cause severe and persistent pollution to surrounding water bodies and soil ecosystems, posing threats to human health [7–9].

In recent years, the global demand for non-ferrous metal resources has continued to grow rapidly, accompanied by an annual increase in the discharge of related industrial wastewater, primarily including wastewater from non-ferrous metal mining, mineral processing, and smelting [10]. The majority of this wastewater originates from mineral processing operations dominated by flotation, followed by overflow

water generated during the thickening and dewatering of concentrates and middlings [11–13]. This type of wastewater features complex and variable compositions, containing numerous toxic and hazardous substances. Due to differences in separation techniques for different ores, the types and concentrations of pollutants in the wastewater also vary accordingly [14]. Wastewater from processes like gravity separation and magnetic separation primarily contains suspended solids as the main pollutant [15,16]. In contrast, flotation processes generate the largest volume of mineral processing wastewater, with residual flotation reagents and metal ions being the predominant pollutants [17,18].

The solid suspended solids (mainly slime particles) present in mineral processing wastewater reduce water transparency, impede photosynthesis in aquatic vegetation, and consequently severely impact the health of aquatic ecosystems [19,20]. Simultaneously, the organic and inorganic reducing agents used in flotation processes lead to increased chemical oxygen demand (COD) and biochemical oxygen demand (BOD) in water bodies [21]. Some of these reagents possess certain toxicity, posing potential ecological and health risks if discharged into the aquatic environment [22]. Furthermore, heavy metal ions in the wastewater are resistant to biodegradation, can persist in water bodies for extended periods, and gradually accumulate through the food chain, ultimately posing serious threats to human health and the ecological

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environment [23,24].

Therefore, developing efficient, economical, and environmentally friendly technologies for removing pollutants from mineral processing wastewater is of significant practical importance for protecting the ecological environment, ensuring production safety, and achieving cleaner production and sustainable development in the mineral processing industry. This review aims to systematically summarize various technologies currently employed for treating pollutants in mineral processing wastewater, including traditional methods such as acid-base neutralization, adsorption, chemical oxidation, biological methods, combined treatment technologies, as well as emerging treatment technologies. It will delve into their mechanisms of action, application status, and development trends, and provide a comparative analysis of the advantages and disadvantages of different technologies. The objective is to offer valuable insights for researchers and engineers in this field and to discuss future technological development directions.

## 2. General principles for wastewater treatment in mineral processing

In the treatment of wastewater from mineral processing plants, establishing scientific and rational principles is crucial for achieving economic, efficient, and environmentally friendly goals [25,26]. Firstly, priority should be given to fully utilizing the natural purification capacity of tailings ponds, where wastewater undergoes initial pretreatment through clarification and natural sedimentation. If the natural purification effect fails to meet discharge or reuse standards, artificially enhanced measures must be implemented, involving methods such as the addition of flocculants or chemical agents for advanced treatment. When selecting chemical agents, the principles of simplification and synergy should be followed, prioritizing the use of single agents. When complex water quality necessitates combination, the types of agents should be strictly controlled to avoid system redundancy. Furthermore, the selection criteria for agents must balance environmental friendliness with technical and economic feasibility, favoring those that are non-toxic or low-toxicity, highly efficient, low-polluting, readily available, and cost-effective. Additionally, a core principle emphasizes the in-depth analysis of wastewater composition, advocating for the utilization of its intrinsic physicochemical properties to achieve “treating waste with waste” and comprehensive management. This approach promotes the development of wastewater treatment processes towards resource recovery, waste reduction, and systematic integration [27,28]. Table 1 summarizes different mineral processing methods, their typical reagents, the main pollutants generated (e.g., heavy metal ions, processing reagents, suspended solids, cyanides, acids/alkalis, etc.), and the key characteristics of the wastewater (such as pH range, chemical

**Table 1**

Summary of wastewater pollutant characteristics from different mineral processing techniques.

Mineral Processing Method	Primary Reagents/ Conditions Used	Main Pollutants in Wastewater	Typical Wastewater Characteristics
Flotation	Collectors, Frothers, Depressants	Organic flotation reagents, heavy metal ions, suspended solids	High COD/BOD, contains characteristic organic compounds, often alkaline pH
Gravity Separation	Water (as medium)	High concentration of suspended solids	High turbidity, relatively low chemical contamination
Magnetic Separation	Water, possible acid/alkali cleaning	Magnetic particles, suspended solids	Contains magnetic substances, possible abnormal pH
Acid Leaching	Sulfuric acid, Hydrochloric acid, etc.	High concentration of metal ions (Cu <sup>2+</sup> , Ni <sup>2+</sup> , etc.)	Low pH, high salinity, high metal content

oxygen demand/biochemical oxygen demand values, etc.).

Moreover, leveraging technological advancements in the field of mine intelligence, artificial intelligence (AI) is demonstrating significant potential in mineral processing wastewater treatment. Through deep mining and modeling of wastewater quality data, chemical dosage, and treatment efficacy using intelligent algorithms, AI enables accurate prediction and optimized control of the treatment process. For instance, machine learning models can dynamically predict effluent indicators and intelligently adjust flocculant dosage, ensuring compliance with standards while reducing chemical consumption [29,30]. Intelligent diagnostic systems can identify equipment abnormalities and process faults in real time, enhancing operational stability. The deep integration of these technologies is driving the transition of mineral processing wastewater treatment from an experience-dependent model to a data-driven intelligent paradigm, providing core support for energy conservation, consumption reduction, and refined management in the treatment process [31].

## 3. Research status of common treatment technologies for mineral processing wastewater

Currently, the mitigation of environmental pollution induced by mineral processing wastewater primarily relies on two core technical approaches: wastewater recycling/reuse and treatment to meet discharge standards [32]. Among these, wastewater recycling/reuse not only substantially reduces the total volume of effluent discharged from mining facilities and enhances the efficiency of water resource circulation but also enables partial recovery and reuse of residual beneficiation reagents in the wastewater [33]. This, in turn, reduces the dosage of fresh reagents required to a certain extent, thereby achieving the dual benefits of “water conservation and reagent reduction”. For instance, Jing et al. proposed a technical scheme of recycling acidic mineral processing wastewater into the flotation circuit for scheelite flotation wastewater treatment [34]. The results demonstrated that this scheme not only significantly reduced the consumption of fresh water resources but also optimized mineral flotation conditions through the acidic environment, improving the grade and recovery rate of roughing concentrates (Fig. 1a). Also, the study conducted by Liu Runqing et al. stands as a typical and representative work [35]. The research team systematically investigated the feasibility of reusing wastewater from a polymetallic sulfide ore processing plant through a combination of laboratory-scale tests and industrial-scale pilot studies. The results revealed that direct reuse of wastewater without adjusting the existing beneficiation reagent regime led to a significant deterioration in flotation separation indicators (e.g., concentrate grade and recovery rate). However, by optimizing and adjusting the reagent proportioning parameters, the interference of recycled wastewater on the flotation process was effectively resolved, enabling stable and efficient reuse of the wastewater. Benefiting from the secondary utilization of residual reagents in the wastewater, the consumption of sodium diethyldithiocarbamate (DDTC) and sodium sulfide (Na<sub>2</sub>S) in the flotation process was reduced by 12.90 % and 18.64 %, respectively. Compared with the conventional flotation process for this type of ore, the water-saving rate of this wastewater reuse process reached 34.62 %, which is equivalent to an annual reduction of 525.60 tons in wastewater discharge. A comprehensive analysis indicates that this technical scheme offers the dual advantages of lowering the production costs of enterprises and reducing pollutant discharge volumes, providing an important practical reference for similar mining enterprises to promote technological transformation toward cleaner production (Fig. 1b).

It is important to note that when the water quality indicators of mineral processing wastewater fail to meet the technical requirements for direct reuse, it is necessary to adopt economically efficient wastewater treatment technologies for advanced treatment [36,37]. This ensures that the treated wastewater either meets the national or local discharge standards for safe discharge or fulfills the water quality

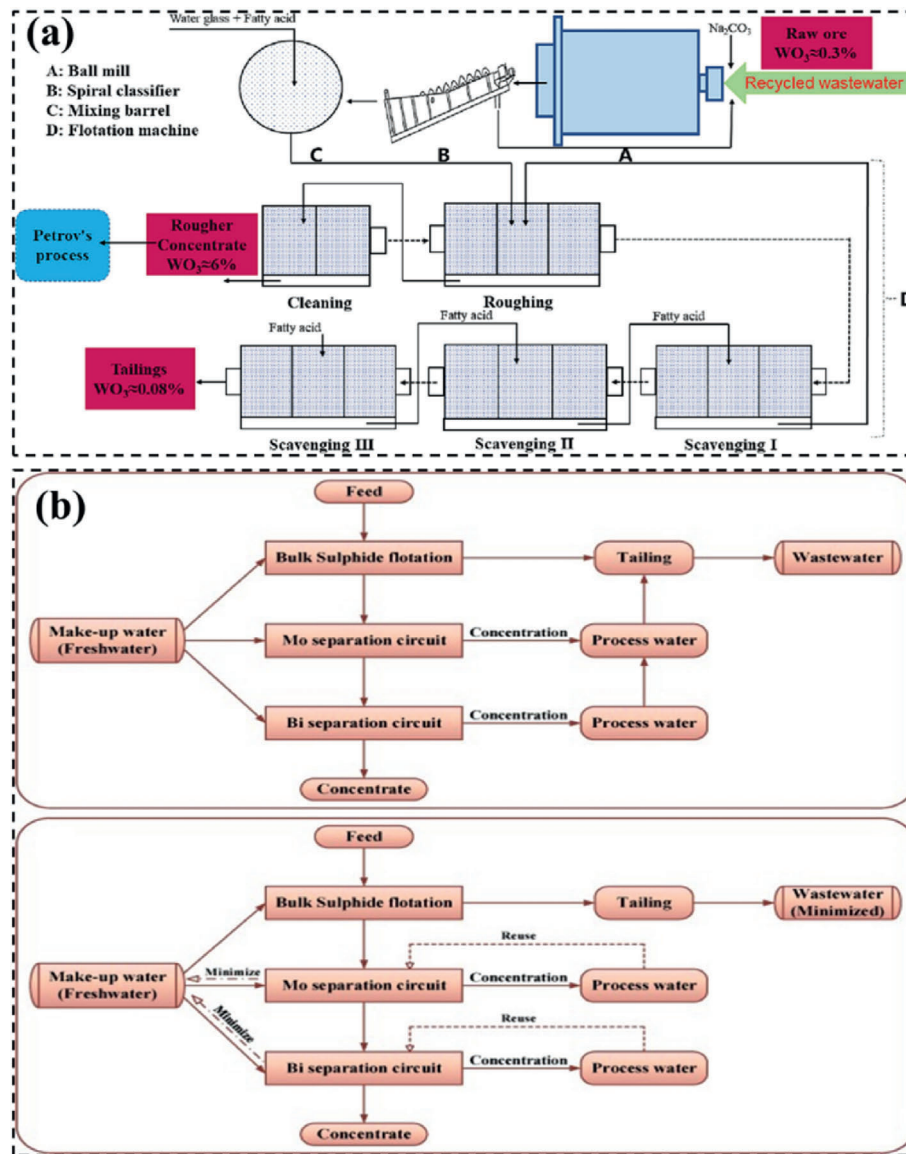


Fig. 1. (a) Flowsheet of the industrial-scale trial of scheelite flotation using recycled wastewater [34]. Copyright 2023, Elsevier. (b) Principled process of industrial scale tests on wastewater reuse [35]. Copyright 2020, Elsevier.

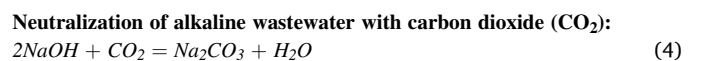
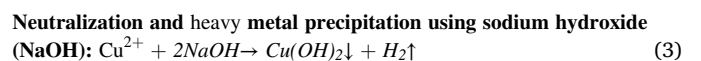
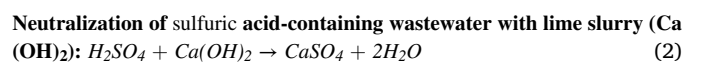
requirements for subsequent recycling, thereby entering the circular utilization system.

### 3.1. Acid-base neutralization method

Within the technical system for mineral processing wastewater treatment, the acid-base neutralization method stands out as one of the most widely applied approaches, owing to its prominent advantages of high economic efficiency, favorable treatment effectiveness, and relatively straightforward operation and management. The core principle of this technology relies on chemical neutralization reactions: by adding acidic or alkaline reagents (such as hydrochloric acid, lime, calcium carbide slag, or acidic/alkaline wastewater from other sources), excess H<sup>+</sup> or OH<sup>-</sup> in the wastewater is neutralized, thereby adjusting the water pH to an appropriate range. Beyond pH balance regulation, its key functions include converting heavy metal ions (e.g., Pb<sup>2+</sup>, Zn<sup>2+</sup>, Cu<sup>2+</sup>) in the wastewater into insoluble hydroxide precipitates for preliminary heavy metal removal [38]. Additionally, the neutralization process effectively reduces the acidity or alkalinity of the wastewater, eliminating the interference of extreme pH values on subsequent treatment

units and creating stable water quality conditions for downstream biological treatment or advanced purification processes (e.g., membrane separation, advanced oxidation) [39]. The typical reaction process can be expressed by the equation as:

**General ionic equation for acid-base neutralization:**  $OH^- + H^+ \rightarrow H_2O(1)$



Extensive research and practical applications of this technology have been conducted by relevant scholars. Silva et al. established a passive pilot-scale acid mine drainage (AMD) treatment system configured as an open-channel structure [40]. The system was filled with various media, including calcite limestone beds (CL-I, CL-II), dolomitic limestone beds

(DL-I, DL-II), as well as mixtures of these limestone materials with natural zeolite (NZ) and functionalized zeolite (FZ). Key water quality parameters monitored included pH, electrical conductivity, total acidity, total alkalinity, and concentrations of aluminum, iron, and manganese ions. Results demonstrated that the DL-I, CL-II, CL-II/NZ, and CL-II/FZ media configurations increased the wastewater pH from 3.3 to 7.9, 8.2, 7.9, and 7.6, respectively. Total alkalinity was elevated from 0 mg  $\text{CaCO}_3\cdot\text{L}^{-1}$  to 20, 107, 42, and 34 mg  $\text{CaCO}_3\cdot\text{L}^{-1}$ , respectively, while total acidity was reduced by 95 %, 91 %, 90 %, and 90 %, respectively (Fig. 2a). Meanwhile, it minimized the volume of discharged wastewater to the greatest extent. Compared with conventional wastewater reuse or end-of-pipe treatment technologies, this approach achieves resource recycling while reducing environmental load, featuring both environmental friendliness and sustainability. Thus, it holds important practical guiding significance for cleaner production practices in the mining and mineral processing industries. Furthermore, Giannopoulou et al. employed the hydroxide precipitation method (a typical application form of the acid-base neutralization method) to treat nickel-containing mineral processing wastewater [41]. Their study showed that when NaOH was added to the nickel-containing wastewater,  $\text{Ni}^{2+}$  combined with  $\text{OH}^-$  to form  $\text{Ni}(\text{OH})_2$  precipitates. At a pH of 10, the nickel removal efficiency reached 99.76 %, demonstrating excellent heavy metal removal performance (Fig. 2b).

However, the acid-base neutralization method also has obvious technical limitations: a large amount of chemical sludge is generated during the treatment process. If such sludge is improperly disposed of (e.g., random stacking, landfilling), it easily poses risks of secondary pollution such as heavy metal leaching. Therefore, supporting processes for sludge dewatering, solidification, and safe disposal are essential [3, 42]. In practical engineering applications, to address the complex composition of mineral processing wastewater (e.g., simultaneous presence of heavy metals, residual reagents, suspended solids), the

neutralization method is often used in combination with oxidation, coagulation-precipitation, and other processes to form a synergistic treatment system. This enables efficient removal of multiple types of pollutants and meets higher discharge or reuse standards.

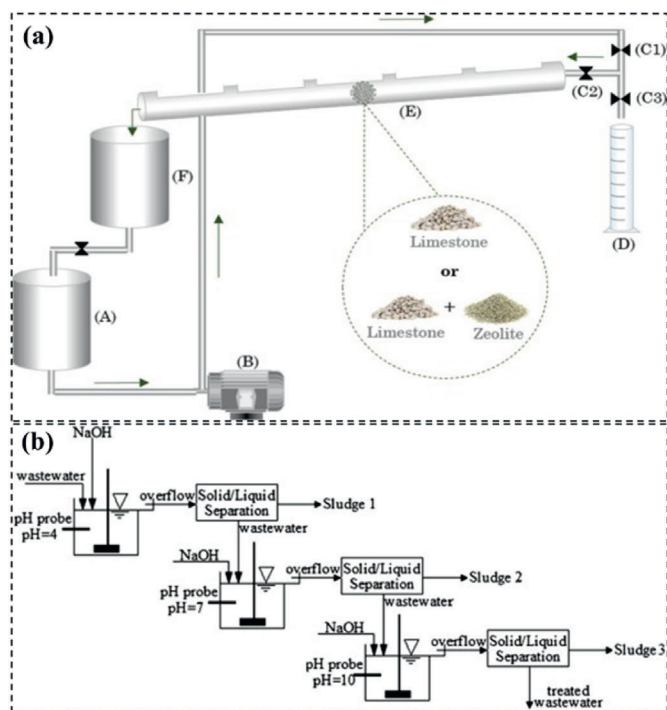
### 3.2. Adsorption method

As an efficient and versatile advanced treatment technology, the adsorption method is extensively employed for removing refractory pollutants—particularly low-concentration heavy metal ions and residual organic reagents—from mineral processing wastewater. Its effectiveness fundamentally depends on the rational design of adsorbent materials, which governs their adsorption performance through controlled structural and chemical properties. Key design strategies—such as tailoring pore size distribution to enhance accessibility, functionalizing surfaces with selective groups (e.g.,  $-\text{NH}_2$ ,  $-\text{COOH}$ ) for targeted binding, and constructing composite interfaces to combine multiple mechanisms—directly determine adsorption capacity, selectivity, kinetics, and reusability. Thus, the purification outcome is intrinsically linked to the synergy between material design and pollutant characteristics, enabling efficient immobilization and removal [43,44].

Over the past few decades, numerous adsorbent materials have been reported for heavy metal removal, including carbon-based materials [45], metal-organic frameworks (MOFs) [46], clay minerals [47], nano-zero-valent iron (nZVI) [48], and various nanocomposites [49]. Biochar is an adsorbent material with excellent performance, yet it exhibits poor selective adsorption capacity. Xu et al. designed a novel porous lotus leaf biochar (MLLB) modified with multifunctional groups of  $\text{PO}_4^{3-}/\text{NH}_4^+$ , which was applied for the removal of beryllium (Be) from beryllium ore wastewater (Fig. 3a). The phosphate, amino, and hydroxyl groups on the surface of MLLB can form complexes with Be, generating beryllium hydroxide ( $\text{Be}(\text{OH})_2$ ) and ammonium beryllium phosphate ( $\text{Be}(\text{NH}_4)\text{PO}_4$ ). This complexation process enables effective adsorption of Be, thereby preventing beryllium exposure during beryllium ore mining [50]. As shown in Fig. 3b, Chen et al. synthesized a novel low-cost tourmaline-montmorillonite nanocomposite via vacuum sintering, which demonstrated a high adsorption capacity of 303.21 mg/g for Pb(II) in aqueous solution [51]. Wang et al. modified UiO-66- $\text{NH}_2$  with  $\text{Ni}_{10-6}\text{Fe}_{2-4}\text{O}_4$  and polyethylenimine to fabricate a magnetic Zr-MOF ( $\text{Ni}_{10-6}\text{Fe}_{2-4}\text{O}_4$ -UiO-66-PEI) for the adsorption of Pb(II) and Cr(VI) [52]. At pH 4.0, the maximum adsorption capacity for Pb(II) reached 273.2 mg/g (Fig. 3c). In parallel, polymeric flocculants have been increasingly integrated into mineral processing wastewater treatment. For example, Zhu et al. synthesized an anionic polyacrylamide with a regular microblock structure [53], which achieved a turbidity removal rate as high as 98.22 % in hematite wastewater treatment (Fig. 3d).

Table 2 systematically summarizes the adsorption-based research on typical pollutants in mineral processing wastewater, clearly presenting the corresponding relationships among target pollutants, high-efficiency adsorbents, and their dominant removal mechanisms.

As a key advanced purification technology, the adsorption method occupies an irreplaceable position in mineral processing wastewater treatment. Nevertheless, it continues to face challenges such as high adsorbent cost, limited regeneration efficiency, competitive adsorption interference, and mass transfer limitations [54]. Future research is expected to focus on the following aspects: (1) developing novel adsorbents with low cost, high capacity, easy regeneration, and environmental compatibility; (2) exploring integrated processes that enable in situ adsorbent regeneration and precious metal recovery; (3) optimizing the coupling of adsorption with coagulation, oxidation, membrane separation, and other technologies to construct efficient and economical integrated treatment systems, thereby addressing the challenges posed by the increasingly complex composition of mineral processing wastewater.



**Fig. 2.** (a) Schematic of the experimental apparatus used in the AMD treatment studies: (A) raw AMD tank, (B) centrifugal pump (C1, C2 and C3) valves for transporting AMD to the bed (D) flow volumetric test beaker, reservoir tank (E) open channel for AMD treatment, and (F) treated AMD tank [40]. Copyright 2021, Elsevier. (b) Simplified flow diagram for the treatment of synthetic polymetallic aqueous solution in three stages [41]. Copyright 2008, Elsevier.

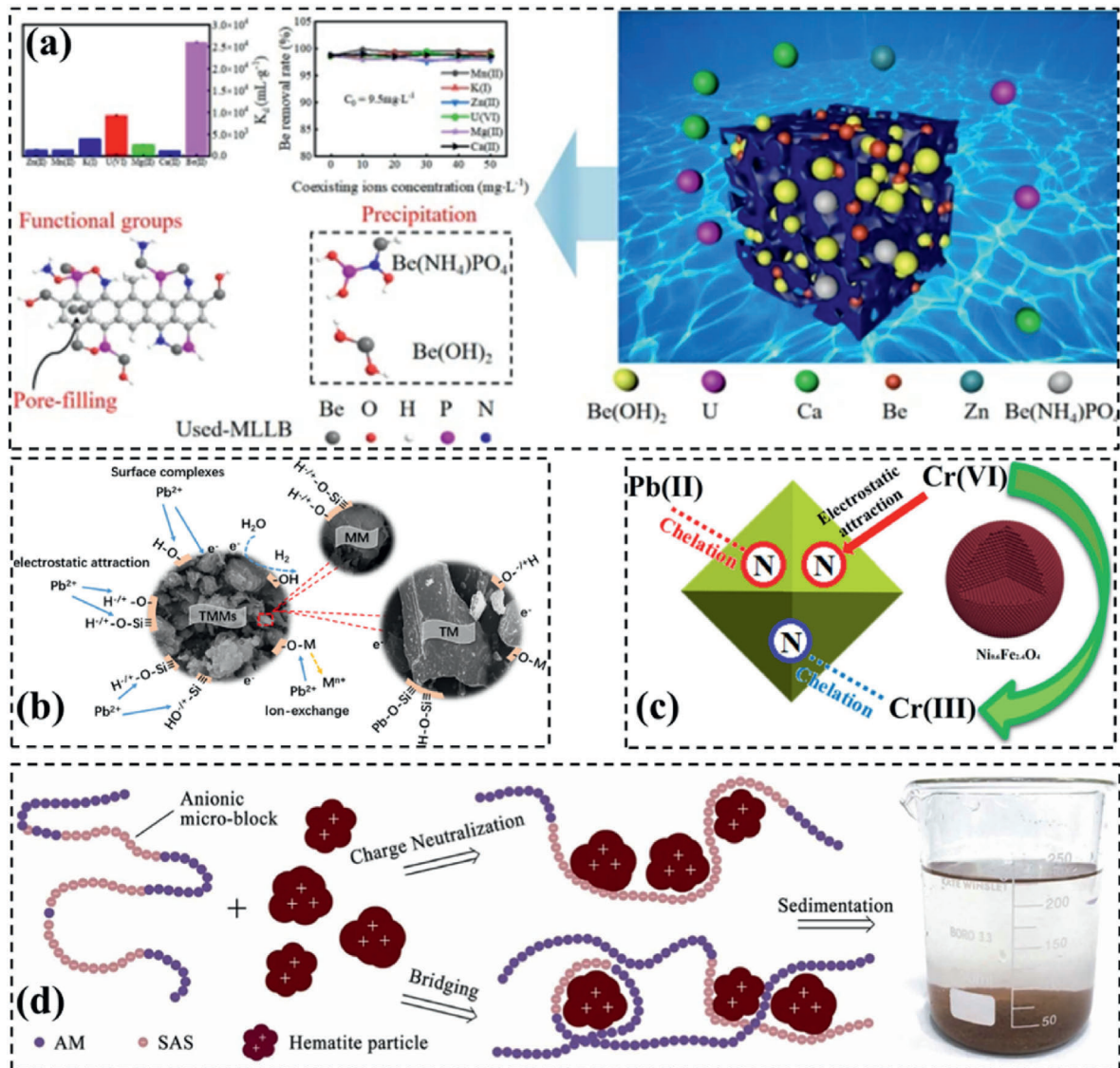


Fig. 3. (a) Mechanism and selectivity of MLLB adsorption of beryllium in solution [50]. Copyright 2024, Springer. (b) Adsorption mechanism of Pb(II) by TMMs [51]. Copyright 2020, Elsevier. (c) Adsorption mechanism of Ni<sub>0.6</sub>Fe<sub>2.4</sub>O<sub>4</sub>-UiO-66-PEI for lead and chromium [52]. Copyright 2021, Elsevier. (d) Flocculation mechanism of APAM-T [53]. Copyright 2024, Elsevier.

### 3.3. Chemical oxidation method

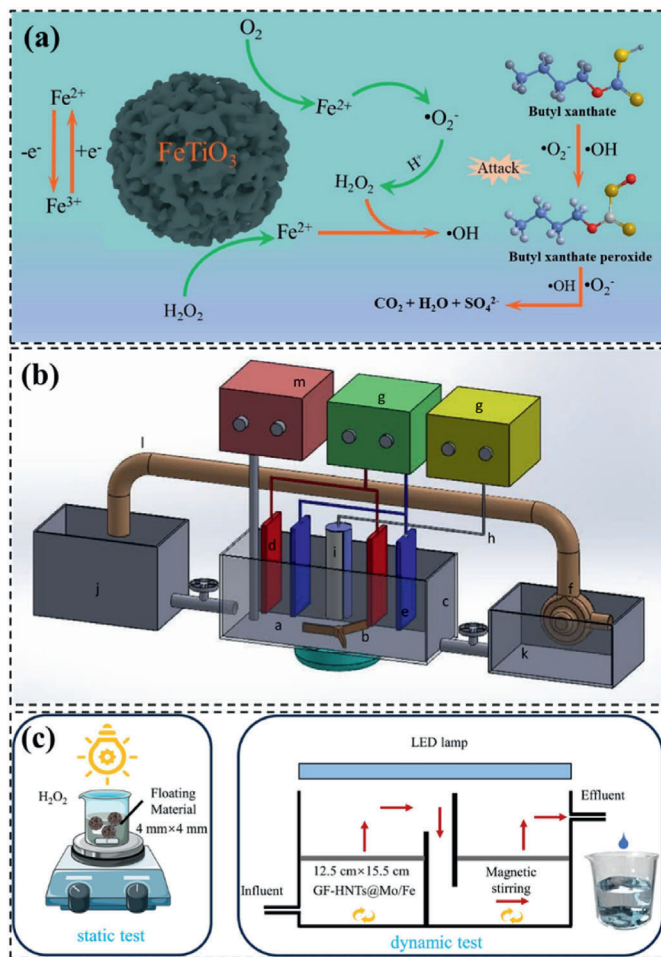
Within the technical system for advanced treatment of mineral processing wastewater, chemical oxidation represents a highly effective and feasible approach. It demonstrates significant advantages in degrading biologically toxic residual organic reagents (such as xanthates, dithiophosphates, and thiocyanates) and removing inorganic pollutants like cyanides. The core mechanism of this technology lies in introducing strong oxidizing agents into the wastewater system or utilizing external energy (e.g., light, electricity, ultrasound) to generate highly oxidative free radicals (e.g., hydroxyl radicals,  $\cdot\text{OH}$ ). These reactive species facilitate the transformation of pollutants—either through direct mineralization of large, recalcitrant organic molecules into harmless end products like carbon dioxide ( $\text{CO}_2$ ) and water ( $\text{H}_2\text{O}$ ), or their conversion into less toxic, more biodegradable intermediate compounds, thereby creating favorable conditions for subsequent treatment stages [55]. As shown in Fig. 4a, Yuan et al. employed natural ilmenite ( $\text{FeTiO}_3$ ) as a catalyst to activate hydrogen peroxide ( $\text{H}_2\text{O}_2$ ) for the degradation of sodium butyl xanthate (SBX) [56]. In another study, Jiang et al. pioneered the use of  $\text{TiO}_2/\text{graphene}$  ( $\text{TiO}_2/\text{G}$ ) composite

photocatalytic materials for the treatment of mineral processing wastewater [57].

Depending on the oxidants used and reaction conditions, chemical oxidation methods can be categorized into conventional chemical oxidation and Advanced Oxidation Processes (AOPs). Conventional methods typically employ traditional oxidants like chlorine ( $\text{Cl}_2$ ) and permanganate ( $\text{MnO}_4^-$ ), with typical applications including the degradation of xanthates in flotation wastewater using permanganate [58]. While operationally straightforward, these methods are limited by relatively low oxidation efficiency and a narrow range of applicable pollutants. In response to these limitations, researchers have developed AOPs with stronger oxidative capacity and broader applicability. Currently implemented AOPs mainly include Fenton-based processes, catalytic ozonation, photocatalytic oxidation, and electrochemical advanced oxidation [59]. Innovative research on chemical oxidation methods for treating mineral processing wastewater has provided crucial support for technological applications. Taking the photo-electrocoagulation-ozone coupling technology (ECOUV) proposed by Shahedi et al. as an example, this technology achieves efficient simultaneous removal of  $\text{CN}^-$  and transition metals such as  $\text{Ni}^{2+}$ ,  $\text{Zn}^{2+}$ ,

**Table 2**  
Adsorptive removal of typical pollutants from mineral processing wastewater.

Category of Target Pollutant	Specific Pollutant Examples	Examples of Optimized Adsorbents	Primary Adsorption Mechanism(s)
Heavy Metal Ions	Cu <sup>2+</sup> , Pb <sup>2+</sup>	Amino-functionalized magnetic chitosan microspheres, EDTA-modified biochar	Surface complexation, Ion exchange
	Cd <sup>2+</sup> , Zn <sup>2+</sup>	Phosphate-modified hydroxalcite, MnFe <sub>2</sub> O <sub>4</sub> nanoparticles	Ion exchange, Surface precipitation
	As(V), Cr(VI)	Zero-valent iron-loaded activated carbon, Polyaniline/graphene composite	Electrostatic attraction, Redox reaction
Organic Processing Reagents	Xanthates	Lanthanum-doped magnetic zeolite, Cationic polymer-modified clay	Electrostatic attraction, Surface complexation
	Dithiophosphates	Hydrophobic activated carbon, COF	Hydrophobic interaction, $\pi$ - $\pi$ interaction
	Fatty acids	Mesoporous silica, MOF	Hydrogen bonding, Pore filling



**Fig. 4.** (a) Reaction mechanism of SBX degradation in FeTiO<sub>3</sub>-H<sub>2</sub>O<sub>2</sub> system [56]. Copyright 2024, Elsevier. (b) Conducting the test in continuous mode [60]. Copyright © 2025 under the terms of the CC BY 4.0 license. (c) Schematic diagram of the experimental setup for AAF-Cd<sup>2+</sup> removal on GF-HNTs@Mo/Fe [61]. Copyright 2025, Elsevier.

and Cu<sup>2+</sup> through the synergistic interaction between electrocoagulation for heavy metal enrichment and photo-assisted ozonation for cyanide degradation (Fig. 4b). The core mechanism lies in the cyclic dynamic synergy of “complexation-dissociation-oxidation-recoagulation”: metal hydroxide flocs generated during electrocoagulation enrich heavy metals while weakening the complexation structure of pollutants, whereas reactive oxygen species produced by photo-activated ozone deeply oxidize the dissociated free CN<sup>-</sup>. This collaborative process significantly enhances the overall removal efficiency of complex pollutants [60]. Regarding material innovation in AOPs, Liu et al. synthesized a stretchable gel-like floating material (denoted as GF-HNTs@Mo/Fe) using halloysite nanotubes (HNTs) as a substrate [61]. This material simultaneously triggers photo-Fenton adsorption and adsorption, enabling synergistic purification of mineral processing wastewater. Performance evaluations showed that GF-HNTs@Mo/Fe exhibits sustained removal capability for aniline aerofloat (AAF), Gd<sup>3+</sup>, and chemical oxygen demand (COD) in both simulated wastewater and actual lead-zinc-copper ore processing wastewater. Even after continuous operation for 288 h, the treatment efficiency remained above 50 % (Fig. 4c). More importantly, this GF-HNTs@Mo/Fe-based floating photo-Fenton-adsorption system effectively addresses two major technical challenges of traditional powdered photocatalysts/adsorbents: firstly, it avoids the solid-liquid separation difficulties inherent to powder systems, reducing subsequent processing costs; secondly, it minimizes performance loss caused by structural damage when powders are formed into blocks or pellets.

In summary, chemical oxidation has evolved from a standalone “end-of-pipe” method to a key unit in integrated treatment systems for mineral processing wastewater. It primarily targets persistent pollutants resistant to conventional methods, enabling water reuse and compliant discharge. As wastewater complexity increases and environmental standards tighten, its role in promoting near-zero discharge will grow. Each advanced oxidation technology presents trade-offs: the Fenton process is mature but sludge-intensive; catalytic ozonation is selective but costly; photocatalysis is green yet limited in efficiency; electrochemical methods are flexible but energy-intensive. Future developments should focus on material innovation and process integration to balance efficiency, cost, and feasibility for treating complex wastewater compositions.

### 3.4. Biological treatment methods

The core mechanism of biological treatment for mineral processing wastewater relies on the metabolic activities of microbial communities (e.g., bacteria, fungi, algae) to achieve synergistic purification of pollutants. On one hand, organic pollutants (such as residual flotation reagents) can be progressively degraded and mineralized into harmless end products like CO<sub>2</sub> and H<sub>2</sub>O; on the other hand, the mobility and biotoxicity of heavy metal ions in wastewater can be reduced through adsorption, precipitation, transformation, or immobilization [62]. The specific pathways mainly include three categories: (1) biodegradation, where intracellular metabolic enzyme systems decompose organic pollutants; (2) biosorption and bioaccumulation, utilizing functional groups (e.g., hydroxyl, carboxyl) on microbial cell walls or intracellular accumulation to immobilize heavy metals; and (3) biotransformation, where highly toxic pollutants (e.g., Cr<sup>6+</sup>, CN<sup>-</sup>) are converted into less toxic forms (e.g., Cr<sup>3+</sup>, NH<sub>3</sub>) via microbial redox reactions [63,64].

Among biological treatment systems, algae-based technologies for heavy metal removal have gained significant research attention in recent years due to their environmental friendliness, high treatment efficiency, and cost-effectiveness. Algae possess three key advantages: a high specific surface area providing ample adsorption sites, abundant functional groups (e.g., -OH, -COOH, -NH<sub>2</sub>) on cell walls enabling complexation and ion exchange with heavy metal ions, and rapid growth rates reducing biomass cultivation costs [65]. These characteristics collectively enhance their heavy metal removal capacity. For instance, a

study by Sun et al. demonstrated that a mixture of *Spirulina platensis* and polyacrylamide (SP-PAM) as an adsorbent system for removing  $Pb^{2+}$  and  $Cd^{2+}$  from simulated wastewater and achieved a maximum adsorption capacity of 337 and 232 mg/g for  $Pb^{2+}$  and  $Cd^{2+}$  in aqueous solutions [66], highlighting its potential for heavy metal immobilization (Fig. 5a).

From a technological application perspective, existing research has largely focused on microbial adsorption of common heavy metals, while reports on biosorption technologies for precious metal recovery remain relatively limited. Although microbial adsorption offers advantages such as low energy consumption and reduced secondary pollution compared to conventional physicochemical methods, its practical application is constrained by complex influencing factors (e.g., water composition, temperature, pH) and incomplete mechanistic understanding. Consequently, most studies remain at the laboratory scale, posing challenges for industrial implementation. Nevertheless, some researchers have advanced biological methods toward practical application through process improvements. For example, Han et al. developed a modified anoxic-oxic biological process for treating cyanide-containing wastewater from gold mines [67]. By targeted acclimation, they successfully enriched functional microbial consortia dominated by *Thiobacillus*, *Truepera*, and *Pseudomonas*, which efficiently degraded  $CN^-$  and  $SCN^-$  in wastewater. Operational data indicated average removal rates of 99.99 % for  $SCN^-$ , 97.54 % for COD, 93.92 % for  $CN^-$ , and 98.92 % for  $NH_4^+-N$ , while gold recovery increased to 91 %, achieving dual goals of pollution control and resource recovery.

Among derivative biological technologies, constructed wetland systems represent a typical ecological treatment approach. Their core mechanism involves synergistic interactions among substrates (e.g.,

gravel, activated carbon), aquatic plants (e.g., reeds, cattails), and microbial communities to purify wastewater. Zhong et al. established pilot and medium-scale multi-substrate constructed wetlands for treating mine drainage (Fig. 5b), demonstrating removal efficiencies of 65.37 % for  $NH_4^+-N$ , 77.92 % for  $NO_3^- -N$ , and 69.00 % for COD, validating their efficacy for low-concentration wastewater [68]. It should be noted that in practical engineering, constructed wetlands are typically not employed as standalone treatments for high-concentration mineral processing wastewater. Instead, they are often used as polishing units following pretreatment (e.g., coagulation-sedimentation) or in scenarios with lower water quality requirements for tailwater reuse, leveraging their low-cost and eco-friendly advantages.

In summary, biological methods represent a promising and sustainable approach for mineral processing wastewater treatment [69]. However, significant challenges remain when addressing complex real-world wastewater: (1) extended start-up periods requiring microbial acclimation and biofilm cultivation; (2) low tolerance of microorganisms to high concentrations of heavy metals, high salinity, and toxic reagents, leading to operational instability under fluctuating water quality; (3) poor biodegradability of high-molecular-weight, complex synthetic reagents (e.g., certain novel collectors); and (4) stringent requirements for precise control of environmental factors such as temperature, pH, dissolved oxygen, and nutrient ratios (C:N:P), demanding advanced operational expertise. Future breakthroughs are expected in three key directions to promote the widespread application of biological methods in mineral processing wastewater treatment (i) developing high-efficiency microbial agents (e.g., genetically engineered strains, composite consortia): to enhance tolerance and degradation efficiency toward toxic pollutants (ii) integrating intelligent technologies (e.g.,

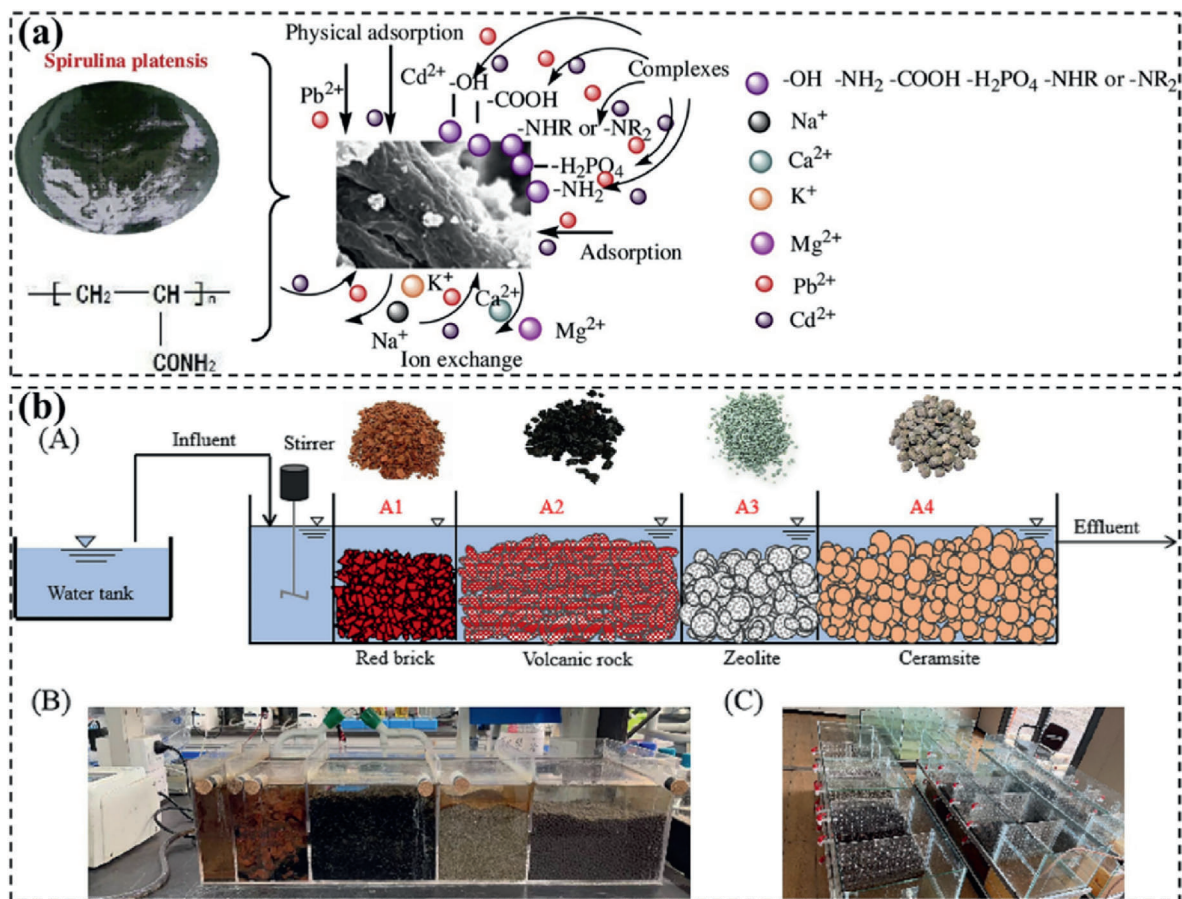


Fig. 5. (a) Adsorption mechanism of  $Pb^{2+}$  and  $Cd^{2+}$  onto *Spirulina platensis* harvested by polyacrylamide [66]. Copyright 2019, Elsevier. (b) Schematic diagram of constructed wetland (A1-A4 represent the unit of brick, volcanic stone, zeolite, and ceramsite, respectively) (A); Installation diagram of a "Lab-scale constructed wetland" system (B); Pilot-scale constructed wetland installation diagram (C) [68]. Copyright 2024, Elsevier.

real-time monitoring, AI-based control); for precise process management and system stability; and (iii) advancing the coupling of biological methods with physicochemical techniques (e.g., adsorption, advanced oxidation) to form complementary integrated processes capable of addressing complex wastewater treatment needs. As these technologies mature, biological methods are poised to play an increasingly vital role in the field of mineral processing wastewater treatment [70–72].

### 3.5. Emerging treatment technologies

Current research on emerging treatment technologies for mineral processing wastewater is accelerating innovations centered on the core objectives of “efficient purification – resource recovery – intelligent regulation.” These technologies are progressively overcoming the limitations of conventional methods in terms of treatment efficiency, resource utilization, and operational stability, offering new pathways for the advanced treatment and recycling of complex mineral processing wastewater.

Among advanced oxidation processes, plasma oxidation has emerged as an effective method for degrading refractory organic flotation reagents due to its strong oxidizing capacity and broad-spectrum activity. For instance, researchers employed dielectric barrier discharge plasma to activate peroxymonosulfate for the synergistic degradation of potassium ethyl xanthate in mineral processing wastewater [73]. This technique generates various reactive oxygen species through high-voltage discharge, enabling rapid degradation and complete mineralization of pollutants, thereby addressing the inefficiency of conventional oxidation methods.

The development and application of novel adsorption materials are increasingly focused on integrated “targeted removal – resource recovery” objectives. Among these, selective ion-exchange resins [74], molecularly imprinted adsorbents [75], and metal-organic framework (MOF)-based composites have shown outstanding performance. For instance, selective ion-exchange resins designed for specific heavy metal ions (e.g.,  $\text{Cu}^{2+}$ ,  $\text{Ni}^{2+}$ ,  $\text{Au}^{3+}$ ) in mineral processing wastewater enable efficient separation of heavy metals through specific binding between functional groups and target ions. The resins can be regenerated via elution and reused, while the recovered metal ions can be recycled as raw materials in smelting processes. This approach significantly enhances resource circulation efficiency and avoids the resource waste and secondary pollution associated with the conventional “adsorption-landfilling” model of adsorbent use.

The development of novel adsorbent materials increasingly emphasizes the integration of targeted removal and resource recovery. Ion-exchange resins, molecularly imprinted adsorbents, and metal-organic framework materials have demonstrated outstanding performance. For example, ion-exchange resins designed for specific heavy metals achieve highly efficient separation through specific interactions between functional groups and target ions [76]. These resins can be regenerated via desorption for repeated use, while the recovered metals serve as raw materials for smelting, significantly enhancing resource cycling efficiency.

In the realm of electrochemical technologies, capacitive deionization removes ions via electrosorption on electrode surfaces, offering advantages such as low energy consumption, chemical-free operation, and flexible performance [77]. It can function as a core unit for advanced desalination and precise heavy metal recovery in mining wastewater.

As shown in Fig. 6, artificial intelligence and digital twin technologies are shifting treatment systems from experience-based operation to data-driven optimization [78,79]. By establishing databases linking process parameters to treatment outcomes and developing predictive models through machine learning, accurate forecasting and dynamic optimization of treatment processes become feasible. Intelligent dosing systems adjust chemical inputs based on real-time water quality. For example, in treating andesite marble processing wastewater, Esra et al. developed an ANN-MLP model to predict final turbidity and optimize

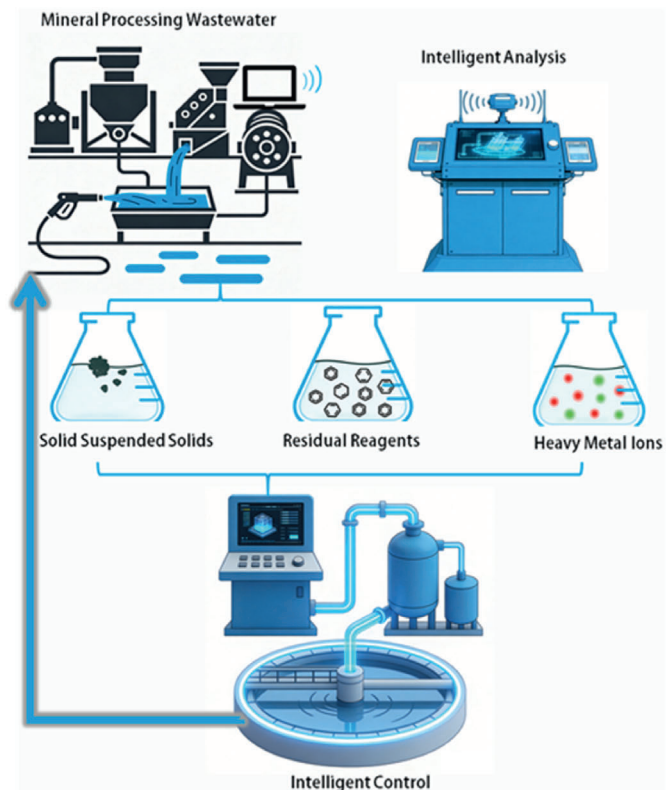


Fig. 6. Intelligent categorized treatment and quality-based reuse system for mineral processing wastewater.

treatment parameters. Using inputs such as coagulant type, dosage, mixing time, settling time, mixing speed, and pH, the trained model accurately predicts performance under different conditions in 45–60 s, streamlining both experimental and operational processes [80]. Also, the digital twins simulate operational conditions to support process optimization and fault prediction [80].

In summary, through interdisciplinary integration, emerging treatment technologies are gradually forming an integrated system oriented toward “efficient purification – resource recovery – intelligent regulation.” As these technologies mature and are applied in combined processes, they are expected to shift the goal of mineral processing wastewater treatment from mere “compliance discharge” to higher objectives such as “near-zero discharge – recovery of valuable components – circular economy,” thereby providing core technical support for the green and low-carbon development of the mineral processing industry.

### 3.6. Comparative analysis and technology selection

To facilitate a clear understanding of the characteristics and applicable scenarios of different technologies, this study systematically compares mainstream approaches—including adsorption, advanced oxidation, and biological methods—across multiple dimensions such as capital cost, operating expenses, scalability, technology readiness, resource recovery potential, and key limitations (Table 3). Based on practical engineering needs, this section further proposes technology selection guidelines tailored to different wastewater qualities and treatment objectives, aiming to support process design and optimization.

## 4. Summary and outlook

The efficient purification and resource utilization of mineral processing wastewater are crucial for reconciling mining development with

**Table 3**  
Comprehensive comparison of major treatment technologies for mineral processing wastewater.

Technology Category	Operating Cost	Scalability	Technology Readiness Level	Resource Recovery Potential	Key Limitations
Adsorption	Medium (regeneration/replacement)	Medium–High (modular design)	Widely applied industrially	Medium–High (selective metal recovery)	High adsorbent cost, competitive adsorption, difficult regeneration
Advanced Oxidation Processes	High (chemicals, energy)	Medium (condition-sensitive)	Some engineered systems	Low (focus on degradation, limited recovery)	High operating cost, potential by-products, pH sensitivity
Biological Treatment	Low (low energy)	Medium–High (scalable)	Conventional methods mature	Medium (biomass/metal recovery possible)	Slow startup, sensitive to toxicity, strict environmental controls
Membrane Separation	Medium (energy & cleaning)	Medium (fouling-limited)	–	Medium (water & concentrate recovery)	Membrane fouling, concentrate disposal, high capital cost
Electrochemical Technologies	Medium–High (electricity)	Medium (electrode-size limited)	Some pilot-scale	Medium–High (direct metal recovery possible)	Electrode degradation, high energy use, scale-up challenges
Coagulation-Sedimentation	Low (chemical cost)	High (easy to scale)	Widely adopted	Low (limited sludge resourceability)	Large sludge volume, low efficiency for soluble pollutants

ecological conservation and for driving the industry's transition toward green sustainability. Currently, treatment technologies have evolved into a diversified system characterized by “conventional processes as the foundation and emerging technologies as breakthroughs.” Looking ahead, mineral processing wastewater treatment will revolve around the core principle of “graded treatment and quality-based reuse,” aiming to construct intelligent, integrated systems through multi-technology coupling. Key future directions include:

**Technology Integration and Optimization:** Guided by the logic of “pretreatment–advanced purification–resource recovery,” hierarchical combinations of technologies such as advanced oxidation processes, membrane separation, and precision adsorption will form closed-loop processes capable of simultaneously recovering water, salts, and heavy metals.

**Intelligent Process Enhancement:** Leveraging IoT, machine learning, and digital twin technologies to develop predictive models for treatment processes will enable dynamic optimization of parameters such as chemical dosing and membrane flux, facilitating a shift from experience-based control to data-driven management.

**Strengthened Resource Circulation:** Emphasizing “waste-treating-waste” strategies and enhancing resource recovery—for instance, utilizing tailings to prepare adsorbents or improving the recovery rate of precious metals from wastewater—can transform treatment units from cost centers into resource value-added hubs.

In conclusion, future advancements must transcend the limitations of single-technology approaches. Through multidimensional innovations in technology integration, intelligent regulation, and resource circulation, the industry can transition toward a circular economy model characterized by water reuse, comprehensive recovery of valuable components, and near-zero pollutant discharge.

#### CRedit authorship contribution statement

**Xinkai Shen:** Writing – original draft, Project administration, Investigation, Conceptualization. **Pengsheng Wang:** Writing – review & editing, Investigation, Funding acquisition, Conceptualization. **Shusheng Qiu:** Writing – original draft, Investigation. **Zhihui Liu:** Writing – original draft. **Junqi Guan:** Writing – review & editing. **Hailong He:** Writing – review & editing.

#### Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

#### Acknowledgments

The authors acknowledge the financial support from the National Key Research and Development Program of China (2023YFC3709900).

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