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A Short Review on Mining and Mineral Engineering: From System Integration to Green and Intelligent Technologies

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ABSTRACT

Driven by the continuously growing global demand for strategic mineral resources and the progressive depletion of easily accessible ores, the mining and mineral engineering sector is undergoing a profound transformation from traditional high-energy, extensive models toward intelligent, refined, green, and low-carbon directions. This paper systematically reviews the core development trends in the field in recent years, covering three major aspects: the design and application of Integrated Mining and Mineral Processing (IMM) systems, which optimize overall energy consumption by breaking the boundaries between mining and processing; the horizontal empowerment of artificial intelligence (AI) across the entire chain of exploration, mining, and mineral processing, promoting intelligent decision-making and unmanned operations; and green extraction technologies for complex resources (refractory ores and electronic waste), along with key technological breakthroughs in energy-efficient comminution, intelligent sorting, novel reagents, and tailings resource utilization. The coupling of multiple technologies and whole-process intelligent control is becoming the core driving force for promoting efficient, safe, and green development in the mining industry.

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Introduction

Mining and mineral processing serve as the cornerstone of modern industry, providing indispensable raw materials for the global economy. However, this sector is also the second-largest industrial energy consumer worldwide, facing severe challenges such as the depletion of easily accessible ores and the continuous decline in head grades (e.g., the average grade of copper ore has fallen below 0.5%). In the traditional "crushing-grinding-flotation" process, the comminution stage accounts for over 50% of the total plant energy consumption and generates substantial tailings, posing significant environmental risks [1,2]. In recent years, technological breakthroughs have offered new possibilities to address these contradictions, primarily in three directions: system-level integration, digital technology penetration, and green technology innovation. This paper aims to synthesize macro-level trends with micro-level technological advances, reviewing important research outcomes from 2019 to 2025 in areas such as integrated mining and processing, AI empowerment, green extraction of complex resources, and key unit technology breakthroughs.

Integrated Mining and Mineral Processing (IMM) Systems: The Physical Foundation for Whole-Process Energy Optimization

Under the traditional model, mining (blasting, transportation) and mineral processing (crushing, grinding, separation) are treated as relatively independent stages. Recent research indicates that breaking the boundaries between these two stages to construct an Integrated Mining and Mineral Processing (IMM) system is key to achieving holistic energy efficiency optimization [3].

The core concept lies in recognizing that upstream blasting outcomes directly affect downstream comminution energy consumption. Studies have shown that in hard rock mine production chains, comminution accounts for over 53% of total energy consumption, yet its energy utilization efficiency is extremely low (3–5% for crushing, approximately 1% for grinding) [4]. By optimizing blasting parameters to generate more micro-cracks during the mining stage, the energy required for subsequent crushing and grinding can be significantly reduced, achieving overall energy savings through "replacing grinding with blasting" [5].

Modern IMM systems are entering a new phase, involving not only physical parameter matching but also the integration of computer simulation and real-time data analysis. By establishing a digital twin system linking the ore body model to the processing plant, mining plans and process parameters can be dynamically adjusted based on real-time variations in ore characteristics, maximizing resource utilization and minimizing production costs [6].

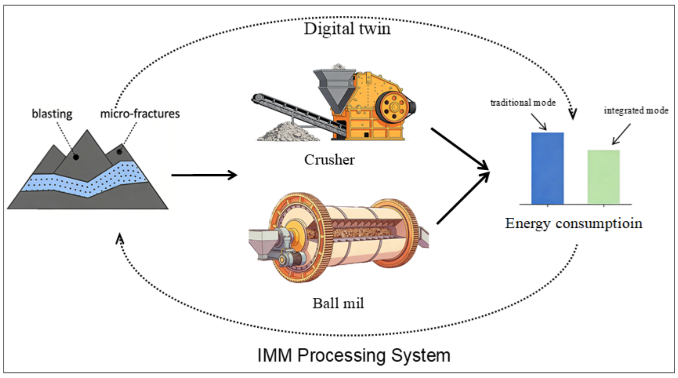

Figure 1: Integrated Mining and Mineral Processing System

Artificial Intelligence and the Transformation Towards Whole-Process Intelligence

If IMM achieves vertical integration of physical processes, artificial intelligence (AI) is horizontally empowering various stages, including exploration, mining, mineral processing, and even equipment maintenance [7].

In the resource exploration phase, machine learning algorithms (e.g., random forests, support vector machines) are widely applied in mineral prospectivity mapping (MPM). Compared to traditional geostatistics, AI can process massive volumes of multi-source geological data, more accurately identify mineralization anomalies, and reduce exploration risks [8,9].

In mining operations, AI-driven autonomous haul trucks and automated drilling rigs have become standard features in modern mines, enhancing operational safety and optimizing haulage routes. More importantly, deep learning-based predictive maintenance systems can analyze equipment vibration, temperature, and other data to provide early warnings of potential failures, significantly reducing unplanned downtime [10].

In mineral processing, AI applications are most intuitive. Traditional flotation relies on manual observation of froth conditions, whereas systems based on machine vision and deep learning can analyze froth color, size, texture, and flow velocity in real-time, automatically adjusting reagent dosages and aeration rates to ensure optimal concentrate grade and recovery [11]. Furthermore, in crushing and grinding circuits, machine vision and deep learning-based load optimization systems have been deployed industrially. By analyzing vibration spectra and power signals to adjust crusher discharge settings in real-time, these systems have reduced fluctuations in product size distribution by over 30% [12].

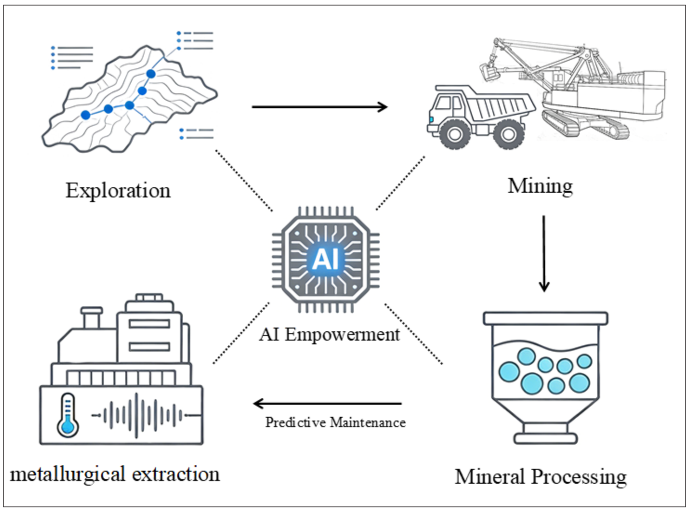

Figure 2: AI Application Framework in Mineral Processing

Green Extraction and Recycling of Complex Resources

Faced with the reduction of easily processable resources, the engineering community is focusing on developing technologies for the economic and environmentally friendly treatment of complex materials.

Pretreatment of refractory ores is a key area. Taking refractory gold ores as an example, gold is often encapsulated within sulfides such as pyrite and arsenopyrite, resulting in very low direct leaching rates. Industrial pretreatment technologies such as pressure oxidation (POX), bio-oxidation, and roasting are used to destroy the sulfide lattice, exposing the gold [13]. In recent years, these technologies have been moving towards milder and cleaner approaches. For instance, ultrafine grinding creates strain and defects on mineral surfaces, and novel environmentally friendly lixiviants (e.g., glycine, thiosulfate) are being explored to replace toxic cyanide, reducing environmental risks [14]. Concurrently, microwave-assisted comminution has achieved progress in engineering applications, with continuous microwave treatment units reaching pilot scale (10 t/h). For sulfide-bearing gold and copper ores, microwave treatment can reduce the Bond Work Index by 3–9% [15].

The concept of a circular economy in mining is gaining increasing attention, manifesting in two main aspects: first, the resource utilization of mine solid wastes (tailings, waste rock), such as recovering valuable metals, producing construction materials, and geopolymers; second, focusing on "urban mines," particularly the recovery of metals from waste electrical and electronic equipment (WEEE) [16]. The grades of gold, silver, copper, and rare metals in e-waste far exceed those in natural ores. Developing efficient, low-energy hydrometallurgical and bioleaching technologies has become a crucial pathway to secure critical metal supply chains [16].

Significant advances have been made in tailings resource utilization in recent years: valuable components such as gold, silver, and rare earths are recovered from old tailings through chlorination roasting-leaching or bioleaching; iron tailings are used to produce autoclaved aerated concrete and geopolymers; utilizing calcium and magnesium silicates in tailings for mineral carbonation achieves CO2 sequestration and tailings stabilization, with one nickel tailing absorbing 16~91 kg of CO2 per ton under ambient temperature and pressure [17,18].

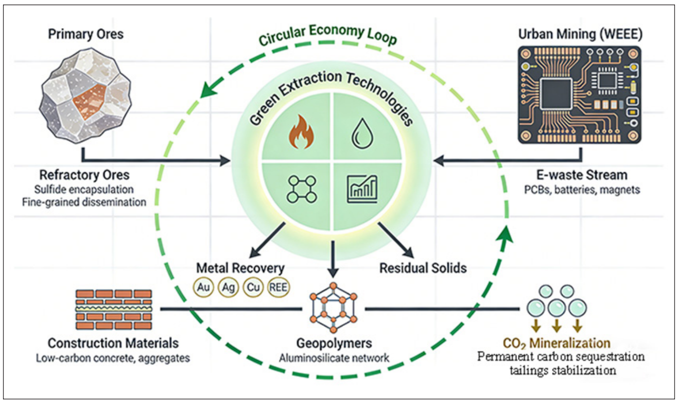

Figure 3: Pathways for Green Extraction and Circular Utilization

Key Unit Technology Breakthroughs

Against the backdrop of macro-level system integration and intelligent empowerment, several key unit technologies have also achieved substantial progress.

Comminution and Classification Technology

High-Pressure Grinding Rolls (HPGR) have been extended from copper and gold ores to platinum group metals and iron ores. Novel wear-resistant stud materials have extended roll surface life to over 12,000 hours. Combined with dynamic classification and edge recirculation, throughput has increased by approximately 30%, while The wear life of the roller surface has been optimized to reach 14,600 hours [19]. The combined application of microwave and high-voltage electrical pulse fragmentation is emerging as a research hotspot, enabling selective liberation. A 2024 study indicated that Combined processing can effectively improve the liberation degree of ores [20].

Intelligent Sorting and Novel Reagents
The integration of multi-sensor technologies (e.g., XRT + LIBS) with AI-driven real-time decision-making has significantly improved waste rejection rates. In novel flotation reagents, nano-collectors have shown enhanced collecting ability for fine particles (<20 μm). In laboratory studies, the recovery of fine molybdenite increased from 76.13% to 83.36% using a nano-collector, increasing the average Mo recovery rate by 7.23% [21].

Solid-Liquid Separation and Tailings Dewatering
High-pressure filtration technology is advancing towards larger scales and automation, with filter cake moisture stably controlled at 12–15%. The solid concentration of copper tailings reached 83.1 wt%, and that of nickel tailings reached 87.9 wt% [22]. The medium grade iron ores contain high ultrafine fractions of soft slime which result in poor dewatering characteristics., Starch-based graft copolymer flocculants exhibit excellent settling velocity in iron tailings flocculation [23]. In mine wastewater treatment, magnetic mesoporous adsorbents have demonstrated copper ion adsorption capacities reaching 120 mg/g. Membrane distillation and forward osmosis technologies enable water reuse and zero liquid discharge [24].

Conclusion
In summary, the mining and mineral engineering field is undergoing a technological transformation driven by system integration, intelligent empowerment, and green orientation. Integrated Mining and Mineral Processing (IMM) establishes a foundation for physical energy savings by optimizing the whole-process energy chain. Artificial intelligence enables precise decision-making and unmanned operations through data empowerment. Unconventional extraction technologies for complex resources not only expand the boundaries of resource development but also respond to societal expectations for sustainable development.

At the technical level, significant breakthroughs have been achieved in key technologies such as HPGR, microwave-assisted comminution, multi-sensor AI sorting, nano-collectors and nanobubbles, tailings carbonation, and geopolymer preparation. These advances have driven reductions in comminution energy consumption of over 20%, waste rejection rates exceeding 70%, significant improvements in fine particle recovery, and accelerated progress towards tailings resource utilization and zero discharge.

Looking ahead, researchers and engineers should focus on the coupling of multiple technologies (e.g., integrated microwave-high voltage pulse-grinding systems) and whole-process intelligent control to address the challenges of clean and efficient utilization of low-grade refractory ores, promoting the mining industry towards higher quality and more sustainable development.

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