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# Sustainable Mining and Processing of Mineral Resources

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The global mineral extraction industry is undergoing rapid transformation. Although the main objectives of mining operations are still related to optimizing productivity, eliminating deviations from quality specifications, and ensuring zero accidents, new challenges and restrictions have been added concerning climate change, increased demand, the depletion of reserves, process automation, corporate responsibility, etc. These developments affect mining operations in various ways: coal mines that supply steam power plants must be closed, while new mines, which will produce critical minerals for the ongoing digital and energy revolution, must be opened. Both mine closure and mine development works must take place in a way that ensures the sustainable development of the areas that host or will host mineral extraction and processing operations.

Governments, industrial partners, funding organizations, and academia are looking for strategies and synergies for an economically and socially justified transition to a low-carbon economy, following global sustainability goals and circular economy principles. Developing these strategies requires clarification of how mineral resources are consumed in society, including both in the value chain and the supply chain of the mineral-derived products [1]. At the same time, all the involved parties must try to develop a conceptual framework, which will ensure that the increased demand for critical minerals is met by increasing the rate of exploitation of mineral deposits and secondary sources based on methods and techniques that successfully balance economic growth, the conservation of nature, and the prosperity of local communities. The impacts associated with mineral extraction can be assessed by different methodologies including criticality analysis, material flow analysis, and life cycle assessment, which emphasize different aspects of sustainability. To address sustainability in mineral resources, the discrete activities of mining, processing, manufacturing, distribution, and recycling should be integrated, and each should adopt a variety of initiatives [1].

There are differing opinions regarding the scarcity of mineral resources and their future availability. On one hand, the scarcity of certain minerals like antimony, copper, and zinc raises concerns about the sustainability of current extraction and consumption rates. Estimates suggest that without significant resource-saving measures, it may be impossible for future populations to enjoy the same level of access to these minerals as those in developed countries today. Thus, the implementation of stringent conservation strategies is essential for extending the availability of these resources significantly, even as global demand increases [2]. On the other hand, some argue that concerns about mineral depletion are overstated. Although the lifespan of a mine is relatively short, ongoing mineral exploration and the delineation of new ore bodies have so far kept reserves stable [3]. Deep underground mining has been extensively developed in this direction. One of the main advantages of deep underground mining is its lower environmental footprint compared to shallow mining. However, there are still challenges associated with deep underground mining, mainly the environmental, financial, geological, and geotechnical



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aspects. Solutions could be provided by recent advances in science and technology, such as the integration of mineral processing and mining and the digital and technological revolution [4]. Nevertheless, instead of depletion, environmental, social, and governance issues are viewed as the more pressing challenges, potentially leading to resource conflicts and limiting the conversion of resources into usable reserves [3].

Digital transition in mining, often termed Mining 4.0, represents a significant shift towards integrating advanced technologies to ensure sustainability and efficiency. Mining 4.0 embodies the principles of the Fourth Industrial Revolution, emphasizing the use of "end-to-end" digital technologies to stabilize the mineral sector amidst fluctuating demand and profitability [5]. This transition also aims to enhance environmental safety and mitigate human-made risks by introducing cyber-physical systems that replace traditional physical processes and human labor. While the conservative nature of the mining industry has slowed the adoption of these innovations, the focus is increasingly on energy-efficient and environmentally conscious practices. Techniques such as non-explosive ore fragmentation, low-water automated sorting, and selective metal leaching are examples of how digital technologies can reduce waste and energy consumption, aligning the industry with broader sustainability goals [6]. In addition, artificial intelligence-enabled algorithms recommended by Mining 4.0 can be incorporated into mining fleet management systems (FMSs) to address the high dimensionality, stochasticity, and autonomy needed in increasingly complex mining operations [7].

Focusing on advances in green mining technologies and practices, the key objectives include energy consumption, greenhouse gas emissions, and improved waste management compared to traditional methods. The use of electric vehicles and renewable energy sources in mining operations has resulted in decreased carbon emissions and energy usage across studied sites, enhancing, at the same time, economic efficiency within the mining industry [8].

Moreover, it is worth noticing the growing interest of the mining industry in risk assessment and management issues, which is confirmed by a significant number of recent publications and reports. Both theoretical and application studies have indicated that risk in mining operations should analyze not only the human factor aspects but also the strategic (environmental impact) and operational ones [9].

The environmental impacts posed by mining have necessitated effective waste management and remediation strategies. Monitoring mine dump pollution and managing waste through recycling and reuse can reduce raw material needs and minimize environmental impacts. Legal frameworks and the enforcement of environmental laws in various countries emphasize the need for stringent regulations to mitigate mining-related damage. The review underscores the role of state authorities and civil society in ensuring compliance with these regulations and explores management techniques for controlling the environmental impacts of mine dumps, stockpiles, and tailings, including the monitoring and control of radioactivity [10].

The integration of the circular economy (CE) model into the mining industry is becoming essential for enhancing sustainability and resource efficiency. By adopting the "3R" principles—Reduce, Reuse, Recycle—mining operations can optimize the use of resources, decrease waste generation, and improve the overall economic viability of surface mining projects. Implementing circular practices allows for significant energy savings, better quality control, and the recycling of by-products, which can provide substantial benefits to both the environment and the economy [11]. Sustainable mineral resource management, particularly the recycling of critical raw materials, is a key aspect of this transformation. Increased stakeholder involvement and awareness of CE principles within the mining sector are crucial for advancing these efforts. This shift towards circular practices not only supports the achievement of environmental goals but also contributes to the long-term sustainability and profitability of mining operations [12].

Finally, the phase-out of coal-fired power across Europe is complex, particularly for countries with a deep history of coal mining and reliance on coal for energy. These countries often experience "carbon lock-in," where institutional factors hinder the transition away from coal. Using the Varieties of Capitalism framework, the study of Rentier et al. [13] compares the phase-out processes in Coordinated Market Economies (CMEs) like Germany, Spain, and Poland with those in the Liberal Market Economy (LME) of the UK. In CMEs, factors such as strategic interactions, employment protection, and government ownership have slowed the transition by supporting domestic coal industries through subsidies. In contrast, the UK's market-driven approach facilitated a faster coal phase-out. The qualitative comparison of these countries from 1990 to 2017 demonstrates the significant impact of economic systems on coal phase-out strategies.

In this context, the first article of this Special Issue explores the critical role of minerals in China's energy transition to achieve carbon neutrality by 2060. Using a dynamic stock model, Beibei Che and colleagues examine the future demand and risks associated with 18 essential minerals in energy infrastructure, particularly wind and solar power. The analysis reveals significant potential risks, especially for cobalt (Co) and indium (In), which could hinder the development of electric vehicles and photovoltaics. The study emphasizes the need for early resource security strategies to ensure mineral availability and mitigate supply risks during China's energy transition (Contribution 1).

Pentari et al. investigate lithium content and its leaching characteristics in Greek coal fly ashes. Through extensive analysis, including X-ray fluorescence spectroscopy and sequential extraction methods, they find lithium concentrations ranging from 95 to 256 μg/g, primarily bound within the fly ash matrix. Their findings suggest that 70–90% of lithium remains in the residual fraction, indicating strong binding, which poses challenges for efficient lithium recovery. The study highlights the potential of Greek coal fly ashes as a lithium resource while emphasizing the need for improved extraction techniques (Contribution 2).

Kuzmenko et al. examine the stability of artificial rock masses formed by backfilling mined-out stopes with a viscous fluidal solution in steep ore deposits. The study identifies the challenges posed by exogenous fracturing at the Pivdenno-Belozirske deposit, which impacts the operational stability of mining chambers. By developing an analytical solution to model the penetration of backfilling mixtures into microcracks, the research offers insights into optimizing backfilling procedures required to maintain stability and prevent rock fallouts. The findings are crucial for improving safety in mining operations involving steep ore deposits (Contribution 3).

Cacciuttolo and Alex Marinovic present a case study from Peru, highlighting the benefits of disposing of mine tailings in underground mines as an environmentally sustainable solution. The study discusses various techniques, including hydraulic and cemented paste backfills, emphasizing their effectiveness in reducing acid rock drainage and metal leaching. By limiting the environmental impact, such practices foster better community relations and contribute to the broader goals of green mining. The article provides valuable lessons from practical experiences in Peru, advocating for the wider adoption of these strategies in the mining industry (Contribution 4).

Bazaluk et al. focus on determining safe operational distances for mining equipment when forming internal dumps in deep open pits. By using Slide 5.0 software for numerical modeling, they assess the stability of dump slopes and the safe placement of equipment. The study identifies the geomechanical factors that influence slope stability, with a particular emphasis on the safety margins required for dragline operations. The results offer practical guidelines for the safe development and reclamation of depleted open pits, ensuring both operational efficiency and environmental responsibility (Contribution 5).

Velasquez et al. explore the application of process mining techniques to optimize mine equipment maintenance processes. By analyzing low-level data through discrete-event simulation and process mining, their study identifies inefficiencies and bottlenecks in the maintenance workflow of an underground block-caving mine. The case study demonstrates a significant loss in equipment operating hours and highlights the potential cost savings from process optimization. The research showcases how process mining can offer an unbiased, data-driven approach to improving maintenance processes in the mining industry (Contribution 6).

Kritikakis et al. introduce a novel methodology for detecting unmineable hard rock inclusions and preventing collisions in Bucket Wheel Excavators (BWEs) using electromagnetic inspection and a fuzzy inference system. The study compares two processing approaches (Simple Mode and Advanced Mode), highlighting the advantages of each in different operational scenarios. The findings demonstrate the increased accuracy of the Advanced Mode in detecting hard rock inclusions, contributing to safer and more efficient mine operations. This methodology represents a significant advancement in collision prevention technology for BWEs (Contribution 7).

Andronikidis et al. conduct a geophysical investigation in Western Macedonia, Greece, to enhance geotechnical planning and land reclamation efforts for the Mavropigi open pit mine. The study maps the subsurface conditions, including fault locations and bedrock dip, by employing seismic reflection and electrical resistivity tomography. Moreover, it provides critical insights into the geotechnical challenges of the site, enabling safer mining operations and informed reclamation planning. Integrating geophysical data into geotechnical models underscores the importance of multidisciplinary approaches in sustainable mining practices (Contribution 8). Remaining in the research field of geotechnical stability of mines, Toderaș et al. present a stability analysis of the Gura Roşiei tailings dam in Romania, focusing on its closure, greening, and safety. Using multiple stability assessment methods, the study evaluates the feasibility of raising the dam's height for continued tailings storage. The findings reveal significant stability issues, particularly in seismic conditions, indicating that further storage would pose environmental risks. The research emphasizes the need for careful planning in the closure and reclamation of tailings dams to ensure environmental safety and sustainability (Contribution 9).

Kozłowski et al. analyze the long-term effects of agricultural reclamation on Technosols in a post-mining area in Central Poland. Over 43 years, the study observes improvements in the physical and water retention properties of fertilized Technosols, particularly in the surface horizons. The research highlights the importance of appropriate fertilization in enhancing soil quality, though it also notes the limitations of over-fertilization. The findings contribute to our understanding of the long-term impacts of agricultural practices on reclaimed mine soils, providing guidance for effective land reclamation strategies (Contribution 10). To improve the capacity of restored soils to support vegetation growth, Więckol-Ryk et al. also propose the creation of artificial soils from coal mining waste and other industrial by-products for post-mining land reclamation. Their study, part of the EU-funded RECOVERY project, demonstrates the effectiveness of these soil mixtures in promoting vegetation growth on degraded lands. The two-year field study shows that artificial soils support various plant species, with decreasing soil salinity improving plant diversity. The research offers a sustainable solution for mitigating the environmental impact of coal mining, contributing to the restoration of biodiversity in post-mining areas (Contribution 11).

Spanidis et al. introduce a combined SWOT–AHP methodology for selecting sustainable transformation strategies for surface coal mines. Using a case study from Greece, the research identifies key factors influencing mine closure and post-mining transformation, integrating expert judgment into the decision-making process. The methodology provides a structured approach to evaluating and selecting strategies that balance geoenvironmental and socioeconomic factors, facilitating the sustainable redevelopment of mining sites. This study offers a practical tool for policymakers and industry professionals involved in mine closure and reclamation (Contribution 12). Furthermore, Servou et al. present a geospatial model for selecting optimal post-mining land uses in surface lignite mines, with an application to the Ptolemais mines in Greece. The research develops an algorithm considering physical characteristics like slope and proximity to infrastructure, integrating them with mining-related parameters. By applying a fuzzification algorithm within a GIS environment, the study generates suitability maps for various land uses, including agriculture, forestry, industry, and recreation. The findings demonstrate the necessity of incorporating qualitative information from mining specifications to produce reliable reclamation plans, offering decision-makers a valuable tool for post-mining land use planning (Contribution 13).

Al Heib et al. present a multi-hazard assessment methodology for post-mining land use planning. The study focuses on the interactions between mining, natural, and technological hazards in closed mining sites, emphasizing the need for comprehensive risk management. By considering the cumulative effects of these hazards, the research provides a framework for safer and more sustainable post-mining development. The methodology is particularly relevant for European mining regions, where many mines have closed, and land use planning requires careful hazard assessment (Contribution 14).

Valle Díaz et al. explore the sustainability of informal artisanal mining in the Peruvian Andean region. Through a documentary review analysis, they examine the socio-environmental conflicts and factors contributing to the persistence of informal mining, such as social licenses granted by local assemblies and governmental leniency towards formalization. The study reveals the environmental consequences, including land use changes that displace agricultural activities, and highlights communal agreements that protect critical water resources. This research underscores the complex interplay between informal mining practices and environmental sustainability in rural Andean communities (Contribution 15).

Siontorou's study addresses the challenges and prospects of sustainable transitions in lignite areas, focusing on mine closures and their impact on communities. Using a modified analytical hierarchy process-based methodology, the research highlights four critical areas for a fair development transition: social implications, stakeholder divergence, land use challenges, and sustainability prospects. The study emphasizes the potential of integrating green strategies like circular economy practices with mining operations to enhance sustainability. This approach suggests that coupling traditional mining practices with modern sustainability measures could facilitate a smoother transition for lignite areas facing economic and environmental shifts (Contribution 16).

Finally, leaving the mines' exploitation and rehabilitation and approaching the coal processing and utilization, Vamvuka et al. investigate the co-gasification performance of low-quality lignite with woody wastes, using $CO_2$ as the gasification agent. The study analyzes the reactivity, conversion efficiency, and gas composition of lignite–biomass blends in a fixed bed unit. The results indicate that blending lignite with biomass can enhance gasification efficiency and increase the heating value of the produced gas. The study also examines the role of minerals and the thermal treatment of the blends, finding that certain combinations, particularly those involving ginning cotton waste, exhibit synergy effects that improve gasification outcomes. These findings highlight biomass blending as a potential solution for optimizing lignite gasification processes (Contribution 17).

The above-presented collection of seventeen studies highlights the evolving landscape of the global extractive industry amid profound changes driven by sustainability imperatives, technological advancements, and changing geopolitical conditions. Central to these developments is the dual challenge of meeting the rising demand for critical minerals essential for digital and energy transitions while mitigating environmental impacts and ensuring social responsibility.

The studies address the varying perspectives on mineral resource availability and depletion, highlighting debates on the longevity of reserves and the importance of conservation measures. While concerns about resource scarcity persist, ongoing exploration efforts and technological innovations offer prospects for maintaining stable reserves. Strategies such as deep underground mining and the integration of digital technologies (Mining 4.0) emerge as pivotal in enhancing efficiency and reducing environmental footprints. These innovations not only optimize resource extraction but also support broader sustainability goals by minimizing waste and energy consumption. Although they were not included in the contributions we received in this Special Issue, deep-sea mining and extraterrestrial mining should be added to the innovative actions undertaken to meet the future demand for critical minerals.

Nevertheless, environmental, social, and governance challenges pose significant hurdles that must be addressed to ensure responsible and sustainable mining practices. In this context, the integration of circular economy principles into mining practices emerges as a transformative approach. By emphasizing Reduce, Reuse, Recycle strategies, the industry aims to maximize resource utilization and minimize environmental impact across the entire mine lifespan.

One of the critical themes explored is the transition towards a low-carbon economy, necessitating strategic shifts in mineral extraction and consumption patterns. The studies underscore the complexity of balancing economic growth with conservation efforts and community well-being. This issue mainly concerns regions that have traditionally based their economic and social development on coal exploitation for decades. A key dimension is the selection and spatial distribution of land uses after the closure of mines in a way that covers both the need for ecological restoration and the ability of local communities to maintain a decent standard of living. To this end, research focuses on developing new, sometimes hybrid multicriteria decision methodologies for optimal land use selection, many of them utilizing spatial information derived from geographic information systems.

Overall, the findings underscore the industry's evolution towards greener, more efficient practices aligned with the global sustainability agenda. They advocate for comprehensive strategies that integrate technological innovation, environmental stewardship, and social equity to navigate the complexities of a rapidly transforming mineral extraction landscape. As stakeholders continue to collaborate and innovate, the path toward sustainable mineral resource management becomes increasingly promising yet challenging, requiring ongoing adaptation and collaboration across sectors.

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