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Editorial

Envisioning the Future of Mining, 2nd Edition

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1. Introduction and Scope

The strategic landscape governing extractive industries has undergone a profound transformation in the brief interval since the inaugural edition of this Special Issue in 2024. While the first edition was defined by a conceptual urgency around the global energy transition, the 2025–2026 biennium marks a definitive shift into an implementation-heavy reality. As global markets and regulatory bodies move from rhetoric to action, the mining sector finds itself at the centre of a formidable dual imperative: rapidly scaling production to meet climate goals and meeting the non-negotiable demand for social and ecological integrity.

The current state of the clean energy transition highlights a widening schism between ambition and operational capacity. Historical data show that, over the past years, annual demand for lithium, cobalt, and nickel has surged by 30%, 10%, and 8%, respectively [1]. Looking forward, under the IEA's Net-Zero 2050 scenario, critical mineral production is projected to escalate by an additional 350% by 2030 [2]. This acceleration, however, is occurring against a backdrop of heightened supply chain vulnerabilities and complex geopolitical realities. One must heed the foundational warnings of Owen et al. [3], who argue that the pervasive sense of urgency to secure minerals often threatens to exacerbate social injustices. If Free, Prior and Informed Consent (FPIC) is bypassed in the rush to permit new developments, the industry risks undermining its own long-term viability through systemic conflict.

The mission of this second edition is to demonstrate that, in the 2026 context, technical efficiency is no longer a standalone metric; it is inextricably linked to ethical, environmental, and social performance. This necessity is further underscored by the actualised implementation of the European Critical Raw Materials Act (CRMA) [4,5], which establishes a regulatory "hard floor" for sustainability. This volume maps a future in which the sociotechnical is the default paradigm for mining engineering, reflecting an ontological shift toward the multidisciplinary challenges defined in the following section.

2. The Challenges in Future Mining

Addressing the non-linear challenges of Mining 4.0 requires a departure from traditional siloed thinking. As we move deeper into the era of technological convergence, the industry must adopt a framework that accounts for the sociotechnical entanglement of Nano, Bio, Info, and Cogno (NBIC) sciences [6].

While this framework facilitates the controlled manipulation of interactions between living and artificial systems, it carries the risk of "uncritical technological optimism." We

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must firmly reject transhumanist narratives that suggest society must adapt to technology. Instead, the current paradigm demands an anthropocentric technology configuration in which progress is designed to serve society's specific needs and values.

The multifaceted technical and environmental challenges of the current era reflect this need for human-centric configuration:

- Labour and Human–Machine Interaction (HMI): The transition of labour in Mine 4.0 necessitates a rigorous focus on safety, ensuring that automation augments rather than endangers the workforce.
- Resource Stewardship and Energy Infrastructure: Water conservation and tailings dam integrity remain paramount, particularly given how social conflict translates environmental risk into immense business costs [7]. Furthermore, the sector is evolving from a mere resource extractor to an energy infrastructure custodian, notably through the emerging field of geological hydrogen storage in salt caverns.
- Governance and Legitimacy: One can observe a definitive shift in community governance, moving away from the traditional, often passive Social License to Operate (SLO) [8,9] and mere corporate accountability [10]. The industry is now transitioning toward a co-produced "Social Legitimacy for Mining" (SLM) framework, where local communities actively participate in project design and value distribution.

The regulatory landscape has formalised these requirements, aligning global mineral security with the United Nations Sustainable Development Goals (SDGs) [11–13]. These challenges, while formidable, provide the catalyst for the evidence-based solutions presented by the contributors to this issue.

3. An Overview of the Published Articles

The thirteen articles selected for this edition collectively advance the sociotechnical paradigm, bridging the gap between high-level policy and granular operational reality. These contributions (see the list of contributions below) are organised across four strategic axes, which are introduced in the following paragraphs.

3.1. Axis I: Automation, Technology, and Human–Machine Interaction in Mine 4.0

The integration of digital and physical systems is explored as a renegotiation of the industrial social contract. **Lööw and Johansson** identify eight pivotal conditions changing mining work, emphasising that automation reduces physical strain but fundamentally alters managerial spans of control. **Kolapo et al.** provide a critical overview of HMIs, manifesting the "Cogno" element of NBIC by arguing that the human operator remains essential for maintaining increasingly autonomous robotics. To address open-pit environments, **El Hiouile, Errami, and Azami** propose a multi-layered architecture for real-time surveillance, utilising blockchain and edge computing—the "Info" component of the convergence—to ensure data transparency. Finally, **Rodriguez et al.** explore the "Mining Metaverse," identifying the safety and commercial risks inherent in simulating complex mine scenarios in virtual environments.

Axis I conclusion: Automation is not merely a tool for productivity; it is a fundamental restructuring of the human–industrial relationship, requiring proactive safety and data-privacy frameworks.

3.2. Axis II: Environmental Management, Ecosystem Rehabilitation, and Underground Energy Storage

This axis redefines mining's physical footprint. **Goulart et al.** utilise microbial indicators to track the rehabilitation of soil microbiota following the Brumadinho dam collapse, providing a blueprint for monitoring ecosystem recovery. **Gurgel and Schneider** demon-

strate how superabsorbent polymers (SAPs) can transform the handling properties of iron ore tailings from "cohesive" to "easy flow," facilitating 100% recovery of dam materials. On the energy front, dual studies by **Cai and Yin** and **Huang and Yin** evaluate the transmission, sealing, and design optimisation of salt caverns for underground hydrogen storage in Ontario.

Axis II conclusion: These contributions demonstrate that mine sites can be repurposed as strategic energy assets, transforming the sector into an "energy infrastructure custodian".

3.3. Axis III: Sustainability, Socioeconomic Dynamics, and Community Governance

Social performance is increasingly quantified and formalised. **Eddine** introduces the "Social Legitimacy for Mining" (SLM) framework based on the 2023 Panama mining restrictions, emphasising procedural justice and institutional trust. **Restrepo-Baena et al.** propose a methodology for determining the associative potential of small-scale miners in Colombia to foster economic resilience. Similarly, **Martínez Mendoza et al.** devise a comprehensive action plan for artisanal gold mining sustainability in Antioquia. Finally, **Nieves Pimiento et al.** evaluate the socioeconomic dynamics of coal mining communities, highlighting the critical need to align mining royalties with the SDGs to improve local life expectancy.

Axis III conclusion: Social legitimacy is a co-produced asset; without inclusive governance and equitable wealth distribution, technical operations face insurmountable barriers.

3.4. Axis IV: Circular Economy and Urban Mining of Waste

The final axis examines "Resource Multiplicity" by looking beyond the lithosphere to biological waste streams. **Cescon, Bruschi, and Korf** provide a comprehensive review of the urban mining of bivalve shell waste. Their research suggests that these residues can serve as a sustainable alternative to traditional limestone in alkali-activated cements and mortars.

Axis III conclusion: Urban mining bridges aquaculture and construction, diverting waste from landfills into high-value industrial precursors for the built environment.

The convergence of these diverse fields—from microbial analysis to the Mining Metaverse—shows that the industry's future lies in successfully integrating biological, digital, and social systems.

4. Conclusions

The overarching theme of this Special Issue is one of transdisciplinary convergence. The challenges of the 2025–2026 period have made it clear that the future of mining depends on an integrated approach where engineering, social science, and environmental management are viewed as a single discipline. We can no longer afford to operate within silos. To maintain the momentum of this sociotechnical paradigm, academia, industry, and policymakers must work together to ensure that the minerals of the future are extracted with the highest standards of technical innovation and social justice.

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