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Review paper

TECHNOLOGICAL INNOVATIONS TRANSFORMING THE MINING INDUSTRY: A SHORT REVIEW

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Abstract

The mining industry is undergoing a profound technological transformation driven by the imperative to increase efficiency, enhance operational safety, and meet stringent environmental standards. In response to the growing complexity of ore bodies and rising productivity demands, the sector is rapidly adopting advanced solutions such as wireless initiation systems, NOx-free explosives, autonomous mining fleets, AI-driven analytics, IoT-based condition monitoring, and muon tomography for subsurface imaging. These technologies enable greater precision in drilling and blasting, real-time data integration for decision-making, reduced human exposure to hazardous conditions, and minimized environmental impact. As the industry transitions toward automation and data-centric operations, continuous technological innovation has become essential to ensure the efficiency, sustainability, and competitiveness of modern mining operations.

Keywords*: AI, IoT and automation, NOx-free explosives, muon tomography, sustainable mining*

1. INTRODUCTION

Historically, the mining sector has relied on conventional methods that often compromised safety and environmental standards. However, rising regulatory pressure, deeper ore bodies, and operational cost challenges have fueled a wave of innovation. From wireless blast initiation systems to green explosives and AI-based monitoring, the sector is embracing transformative tools. This paper explores key innovations with a focus on practical applications in surface and underground mining environments.

2. EXPERIMENTAL: Review of Innovations

2.1 NOx-Free Explosives

Traditional AN-based explosives (e.g., ANFO, emulsions) are effective but can emit toxic nitrogen oxides (NOx) during detonation. A study by Araos and Onederra (2017) developed a NOx-free explosive using hydrogen peroxide (HP) and fuel, with void sensitization enabling detonation at low HP concentrations and without confinement [1]. These explosives demonstrated detonation velocities (VOD) between 1,700–6,000 m/s and critical diameters as low as 8 mm. Unlike AN-based products, these HP/fuel explosives maintained detonation even at high water content (up to 56.6 wt.%), offering both safety and environmental benefits [1, 2]. In practice, companies such as Hypex Bio have begun commercial deployment of hydrogen peroxide-based explosives as environmentally responsible alternatives to ANFO, promoting NOx-free blasting in sensitive environments. Their formulations, developed for both surface and underground operations, are designed to meet stringent environmental standards while maintaining competitive detonation performance [3].

2.2 Wireless Initiation Systems

Conventional detonator systems limit blast flexibility and pose risks related to surface wiring. Wireless initiation system eliminates these limitations by using fully programmable, untethered primers. In Teck's Carmen de Andacollo mine in Chile, WebGen™ enabled the detonation of 384 charged holes in a single blast window, quadrupling productivity (400,823 tonnes) compared to conventional methods [4]. It also allowed decoupling of blast timing from weather constraints, thus preserving community relationships and reducing unplanned downtimes. At the Kittilä underground gold mine in Finland, WebGen™ enabled longitudinal uphole stopes to be charged in a double-layer configuration, allowing for larger blast heights and eliminating re-entry in geomechanically unstable zones [5]. In the Sierrita open pit mine in Arizona, the system reduced delays caused by weather and eliminated tie-in time by removing surface wiring, significantly improving blast cycle efficiency and on-bench safety [6]. Meanwhile, at the New Afton block caving mine in British Columbia, WebGen™ allowed adjacent slot blasts to be preloaded and fired separately without exposing personnel to hazardous brow conditions, leading to over CAD 1 million in development cost savings across 18 drives [7]. These cases exemplify the flexibility and reliability of wireless initiation technology in both surface and underground applications, enabling optimized blast designs, increased production rates, and improved safety performance.

2.3 Subsurface Imaging

Accurate visualization of subsurface structures is critical in mass mining methods such as block caving, where ore recovery, dilution control, and geotechnical stability are highly dependent on understanding cave propagation and material flow. Traditional monitoring techniques such as seismic arrays and microgravity surveys are limited by resolution, latency, and coverage. In contrast, novel subsurface imaging technologies, particularly muon tomography, provide high-resolution, real-time insights into cave back evolution, undercut advance, and muck pile morphology [8, 9]. Muon tomography, as presented at MassMin 2024, uses cosmic rays muons and by analyzing their attenuation patterns, 3D density maps of underground voids and materials can be constructed with remarkable precision generating 3D visuals of cave backs and muck piles. Muon tomography was successfully used to detect early cave breakthrough, validate numerical models, and guide production sequences. These results indicate that the technology not only enhances operational safety but also improves ore recovery and reduces overbreak and dilution through timely feedback to engineering and production teams. When integrated with other digital systems, muon imaging becomes a critical tool in building real-time, geotechnically-informed digital twins of active ore bodies [9].

2.4 Integration of IoT, AI, and Automation

The integration of Internet of Things (IoT), Artificial Intelligence (AI), Machine Learning (ML), and automation technologies is increasingly shaping the digital transformation of the mining industry. IoT platforms allow for real-time monitoring of equipment conditions, environmental variables, and geotechnical parameters, supporting predictive maintenance and safety management across all stages of production [10, 11]. When enhanced with AI and ML algorithms, these systems facilitate data-driven decision-making, anomaly detection, and operational optimization, particularly in drilling, hauling, and ventilation control [11, 12]. Autonomous technologies, initially introduced through driverless haul trucks, are now applied in drilling, loading, and even orebody modeling, enabling continuous operation with minimal human intervention [12]. Moreover, the use of low-cost IIoT components such as Arduino-based sensor networks has shown potential for wider adoption in small and mid-scale mining operations, providing affordable solutions for monitoring and automation [13]. Despite infrastructure and cybersecurity challenges, the gradual implementation of these technologies is essential for improving productivity, reducing environmental impact, and enhancing worker safety. The integration of these systems into digital twins enables real-time simulation and optimization of entire mine operations. A digital twin is a real-time, virtual replica of a physical mining operation that continuously receives data from IoT sensors embedded throughout the site. These systems allow operators to simulate scenarios, predict equipment failures, and optimize resource allocation with high precision. For instance, digital twins can model the impact of changes in drilling parameters or ventilation flows before implementing them on-site, thereby reducing risk and downtime. Coupled with remote monitoring, they enable centralized control centers to oversee multiple operations simultaneously, enhancing both responsiveness and safety in hazardous environments. According to the World Economic Forum (2024), companies adopting digital twins have reported up to 30% improvements in predictive maintenance accuracy and significant reductions in unscheduled stoppages [14].

2.5 Sustainable Extraction Technologies

Sustainable extraction technologies are redefining the environmental and economic framework of modern mining by minimizing chemical usage, water consumption, and ecological disturbance. A prominent example is bioleaching, which uses microorganisms to extract metals such as copper, gold, and uranium from low-grade ores. Unlike traditional smelting or cyanidation, bioleaching operates at ambient conditions and generates significantly less waste. Watling emphasizes that biohydrometallurgy has proven particularly effective in processing polymetallic ores where conventional methods are less selective and environmentally taxing [15]. Another emerging technique is electrokinetic in-situ recovery (EK-ISR), which applies low-voltage electric currents to mobilize and extract metals directly from the orebody without physical excavation, thereby preserving surface integrity and drastically reducing energy input. The U.S. Department of Energy's Critical Materials Institute identifies EK-ISR as a key innovation for extracting rare earth elements and other critical materials in a low-impact manner [16]. These technologies are increasingly supported by regulatory frameworks and industry commitments to reduce the carbon footprint and environmental legacy of mining operations.

3. RESULTS AND DISCUSSION

The reviewed technologies show a strong shift toward automation, efficiency, and sustainability in mining. NOx-free explosives offer safe and effective blasting without harmful emissions, addressing both operational and environmental concerns. Wireless initiation systems improve blast flexibility and significantly increase productivity by removing the constraints of wired detonators. Subsurface imaging with muon tomography provides real-time, high-resolution data critical for cave mining, improving ore recovery and geotechnical safety. When combined with digital twins, these systems allow predictive modeling and real-time decision support. IoT and AI enhance equipment monitoring and operational efficiency, while sustainable extraction methods reduce chemical use, energy consumption, and surface disturbance.

4. CONCLUSION

Technological innovation is transforming mining into a safer, smarter, and more sustainable industry. Key advancements in blasting, automation, monitoring, and extraction support higher productivity and reduced environmental impact. As ore bodies become deeper and more complex, continuous adoption of advanced, data-driven, and low-impact technologies will be essential to ensure the long-term viability and competitiveness of modern mining operations.

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REFERENCES

[1] M. Araos, I. Onederra., Cent. Eur. J. Energ. Mater., 14 (4) (2017) 759-774.
[2] G. Rarata, J. Smętek., High-Energetic Materials., 8 (2016) 56 – 62.
[3] Hypex Bio., Sustainable Blasting Solutions: Hydrogen Peroxide Based Explosives, https://www.hypexbio.com, accessed May 24, 2025.
[4] N. Ortega S.M., Case study: Productivity and operational continuity through wireless initiation technology Tech, Carmen de Anadacollo (Coquimbo, Chile)., Orica Blast Engineering., Chile 2024.
[5] J. Näsi., Case study: Double layer blind blast (DLBB) - Webgen™, Agnico Eagle Kittilä mine, Finland., Orica Blast Engineering 2024.
[6] B. Marriott., Case study: Increasing efficiency and safety through wireless blasting technology, Sierita mine, Arizona, United States of America., Orica Blast Engineering 2024.
[7] K. Deneka., Case study: Webgen™ enables safer undercutting in block caving operations, New Afton mine, British Columbia, Canada., Orica Blast Engineering 2023.
[8] Z.-X. Zhang, T. Enqvist, M. Holma, P. Kuusiniemi., Rock Mech. Rock Eng., 53 (2020) 4893–4907,.
[9] D. Schouten, N. Phillips, R. Merrill., Cosmic-ray Muon Tomography: Application in Block Cave Mapping and Modelling., Proceedings of 9th International Conference and Exhibition on Mass Mining, Kiruna, Sweden, 17–19 September 2024.
[10] N. Kyrylenko, V. Korobiichuk, V. Mamrai., IoT for Sustainable Mining: EU-UA Insights on Research, Education, and Business., Zhytomyr Polytechnic State University, Ukraine, 2023.
[11] F. Molaei, E. Rahimi, H. Siavoshi, S. G. Afrouz, V. Tenorio., A Comprehensive Review on Internet of Things (IoT) and its Implications in the Mining Industry., University of Arizona, USA, 2020.
[12] Z. Hyder, K. Siau, F. Nah., Use of Artificial Intelligence, Machine Learning, and Autonomous Technologies in the Mining Industry., Missouri University of Science and Technology, USA, 2023.
[13] I. Vojinović, M. Stojanović, D. Šabaz., IIoT in Mining – Potential Application of "Low-Cost" Sensors and the Arduino Platform., Proceedings - 55th International October Conference on Mining and Metallurgy, 15 – 17 October, Kladovo, Serbia, 2023., DOI: 10.5937/IOC24145V
[14] World Economic Forum., 13 Innovations Making the Mining and Metals Industry More Sustainable, 2024. https://www.weforum.org/stories/2024/11/13-innovations-making-the-mining-and-metals-industry-more-sustainable .
[15] H. R. Watling., Miner. Eng., 75 (2015) 1–17.
[16] U.S. Department of Energy., 2023 Critical Materials Assessment., Critical Materials Institute, Washington, DC, 2023. https://www.energy.gov/eere/amo/critical-materials-institute, accessed May 24, 2025.