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*Research Article*

# Recent Advances in Surface Mining Technologies: Innovation, Safety, Productivity, and Sustainability

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## Abstract

Mining is entering a phase in which decarbonisation, safety, and productivity targets are being pursued through tightly coupled technological and governance changes (Dotsenko et al., 2024; Olsén et al., 2024). This paper develops and applies an integrated socio-technical framework that links major technology families (automation/robotics, AI (artificial intelligence) and digital twins, advanced drilling and blasting, electrification/renewables, and frontier domains such as deep-sea and space mining) to sustainability outcomes across underground, open-pit, processing, and tailings closure contexts (Xiao et al., 2022; Konieczna-Fuławka et al., 2025). Using an interdisciplinary synthesis of peer-reviewed research, industry evidence and policy principles (including Sustainable Development Goals (SDGs) and International Council of Mining and Metals (ICMM) Mining Principles), the study moves beyond a catalogue of innovations by making boundary conditions and second-order effects explicit. As an example, autonomy can reduce exposure to hazards but increase dependence on cyber-physical assurance, connectivity, and functional safety verification; electrification can eliminate underground diesel emissions, yet its net climate benefit and operational resilience depend on charging logistics, power quality, and grid carbon intensity. A maturity–impact mapping is introduced to distinguish scaled technologies from pilots and to prioritise where evidence is transferable versus context-dependent. The framework is grounded in 25 global case studies spanning regions, commodities, and organizational types, enabling comparative interpretation of what works, where, and why. The central contribution is a decision-relevant synthesis that identifies integrated "solution bundles" and the enabling infrastructure, workforce transitions, and governance mechanisms required for credible scale-up, providing a practical agenda for achieving safer, lower-carbon, and socially accepted mining systems.

At the same time, modern safety systems, including collision avoidance technology, wearable smart sensors, slope stability monitoring, fatigue detection, and remote-controlled equipment, help reduce accidents and improve worker safety. Environmental technologies such as energy-efficient equipment, dust suppression, water recycling, waste management, and mine reclamation reduce the environmental impact of mining and promote sustainable development. However, challenges such as high investment costs, cybersecurity issues, data integration, and the shortage of skilled workers still affect the adoption of these technologies. This review presents recent advances in surface mining technologies and explains their contribution to innovation, operational efficiency, safety, and environmental sustainability. It also discusses future trends that can support the development of smart and sustainable surface mining.

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## 1. INTRODUCTION

Surface mining accounts for over 80% of global mineral extraction by volume, supplying vital materials such as copper, lithium, nickel, iron ore, and gold essential for global infrastructure and the clean energy transition. Historically, gains in open-pit mining relied on scaling up physical machinery—deploying larger rope shovels and higher-capacity haul trucks. However, physical scale has reached technological and economic diminishing returns.

The contemporary paradigm shifts the focus from physical scale to precision, automation, and system integration (Xie et al., 2022). By integrating cyber-physical systems (CPS), spatial IoT networks, and electrification, surface mining is transitioning into a closed-loop, data-driven ecosystem (Theissen et al., 2023; Dotsenko et al., 2021)

Technological innovation in mining is not entirely new; mechanization and electrification date back to the Industrial Revolution, but the current wave is unprecedented in both scope and pace. Automation of mobile equipment (haul trucks, drills, and trains), robotics for hazardous tasks, artificial intelligence (AI)-driven analytics, and digital transformation technologies, including Internet of Things (IoT) networks, cloud data platforms, and digital twins, are now being deployed or tested at mine sites globally **(Xiao et al., 2022; Konieczna-Fuławka et al., 2025; Xie et al., 2022).** Autonomous haulage systems (AHSs), for example, have moved hundreds of millions of tonnes of material with zero human driving, improving safety and productivity (Freeport-McMoRan Inc., 2025). Battery-electric vehicles (BEVs) are replacing diesel machinery in some mines, virtually eliminating underground diesel emissions and reducing ventilation requirements (Olsén et al., 2024). Drones and automated robots can map hazardous underground voids or monitor geotechnical risks without exposing workers to danger (Konieczna-Fuławka et al., 2025). These examples illustrate how technology is enabling what the industry terms a move toward “zero harm” and even “zero-entry” mining, in which human presence in high-risk zones is minimized.

## 2. METHODOLOGY

To produce a paper of this breadth, an interdisciplinary research approach was adopted, combining a systematic literature review with case study analysis. The methodology involved several key steps:

Industry and government publications: To incorporate real-world practices and policies, the study reviewed documents from industry organizations (e.g., ICMM), which has published Mining Principles and innovation agendas), government agencies (such as geological surveys or departments of mining in various countries), and international bodies (such as the Intergovernmental Forum on Mining, Minerals, Metals and Sustainable Development (IGF)). Policy frameworks such as the IGF Mining Policy Framework and the World Bank Climate-Smart Mining initiative were examined to understand recommended best practices. The study also included reports from the World Economic Forum and major consulting firms (e.g., PwC Mine 2025 outlook) to identify industry trends and forecasts.

A major component of the study methodology was the identification and compilation of diverse case studies. The study defined a case study broadly as a specific instance of technology implementation or a sustainability initiative in mining, preferably with documented outcomes or lessons learned. More than 30 cases were initially identified across different regions and themes. These were then narrowed to 25 cases that together provide a balanced representation of: Geography—including mining projects or operations in North America, South America, Europe, Africa, Asia, and Oceania. Mining type—covering both underground and open-pit mines. Each case was investigated through multiple sources, including company press releases, news articles, technical papers, and, in some instances, site visit reports or interviews reported in the literature.

Data analysis: Where quantitative data were available, for example, productivity improvements from automation or emission reductions from electrification, these were recorded. The study did not perform new statistical analyses; instead, it synthesized reported metrics. For example, the performance of Rio Tinto’s autonomous haul trucks (one billion tonnes hauled with 15% lower unit costs) and the energy savings from a solar plant at a mine (the 50 MW solar farm at Gold Fields South Deep mine (Kumari, V. (2023)., saving about R123 million annually in electricity costs) are used illustratively in this paper with appropriate citations.

This methodology aims to ensure that the conclusions of the paper are well-grounded in evidence by combining an extensive literature review with diverse case studies and a synthesis of global best practices and frameworks. The interdisciplinary nature of the research team, drawing on expertise in mining engineering, environmental science, and policy analysis, also contributed to a holistic perspective.

## 3. Recent Advances in Surface Mining Technologies

### 3.1 Innovation & Industrial Automation

**Autonomous Haulage Systems (AHS):** AHS technology has reached mass commercial adoption. Ultra-class haul trucks (such as the 290-metric-ton Komatsu 930E-5AT) use multi-modal sensing—combining multi-constellation GNSS (GPS, Galileo, BeiDou), Li DAR, radar, and machine vision—to navigate complex pit routes 24/7 without human intervention. (Kishore, 2025)

**Automated Surface Drilling:** Drill rigs equipped with automated rod-handling and adaptive feed control utilize AI to adjust rotational torque and weight-on-bit in real time based on changing rock hardness, optimizing drill-bit life and blast fragmentation.

**Private Industrial 5G Infrastructure:** Ultra-low latency private LTE/5G communications networks serve as the digital backbone, replacing unreliable Wi-Fi to support edge


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computing, high-throughput telemetry, and real-time remote control across sprawling pit topographies.

### 3.2 Safety & Human Factors

**Core Principle:** Transitioning mine personnel from hazardous, dust-filled active pit faces to climate-controlled Remote Operation Centers (ROCs) located hundreds of miles away.

**Collision Avoidance Systems (CAS - Level 9):** Modern surface fleets deploy ISO 21815-compliant Level 9 collision avoidance. Using Bluetooth beacons, radar, and computer vision, these systems not only alert operators to proximity risks but automatically intervene to slow or stop heavy machinery if a ground worker or light vehicle enters a blind spot.

**Real-Time Pit Wall & Slope Stability Monitoring:** Interfero metric Synthetic Aperture Radar (InSAR), terrestrial radar units, and wireless pore-pressure sensors continuously monitor bench displacement at sub-millimeter precision. Deep learning models analyze displacement velocity to issue early evacuation alerts hours or days prior to slope failures.

### 3.3 Productivity & Operational Efficiency

**Digital Twins & Operational Intelligence:** High-resolution digital replicas of the mine pit are continuously updated using drone-based LiDAR (UAVs). Mine planners simulate pit traffic, shovel-truck queuing, haul road friction, and dust dynamics before executing field modifications. (Kumar, 2024)

**Continuous Surface Mining (CSM):** High-precision mechanical excavators (such as continuous surface miners) excavate material in thin, controlled layers. This process eliminates traditional drill-and-blast requirements in select rock strata, producing uniform particle sizes that bypass primary crushing circuits and significantly lower energy demand.

**Predictive Maintenance via Machine Learning:** Telemetry sensors tracking vibration, hydraulic pressure, thermal gradient, and oil purity feed edge-computing platforms. Machine learning algorithms predict component wear and mechanical fatigue, drastically reducing unscheduled downtime and extending equipment lifespan.

### 3.4 Sustainability & Environmental Management

**Fleet Electrification & Trolley Assist:** Heavy haulage is responsible for up to 70% of direct site-level diesel emissions. Mines are actively transitioning to Battery Electric Vehicles (BEVs) and dynamic trolley-assist overhead power lines. Trolley assist allows ultra-class trucks to climb steep pit ramps on electric power, doubling ascent speeds while eliminating diesel consumption on uphill hauls.

**Sensor-Based Ore Sorting (SBOS):** X-ray Transmission (XRT), Near-Infrared (NIR), and radiometric sensors analyze run-of-mine material on high-speed conveyor belts. High-grade ore is instantly separated from waste rock prior to grinding, reducing water, chemical, and energy usage in downstream mineral processing.

**Tailings Integrity & Progressive Reclamation:** Real-time IoT piezo meters and satellite monitoring track structural stresses in tailings storage facilities (TSFs), while drone multispectral imaging evaluates topsoil health and vegetation coverage during ongoing mine site rehabilitation.

### 3.5 Digital Twin Technology

Digital twin technology creates virtual mine models for planning, equipment monitoring, predictive maintenance, and real-time decision-making, improving productivity and operational efficiency.

### 3.6 Advanced Drilling and Blasting

Advanced drilling and blasting use autonomous rigs, AI-based blast design, and electronic detonators to improve fragmentation, reduce vibration, and enhance safety.

### 3.7 Drone and Remote Sensing Technologies

Drones, LiDAR, and hyperspectral imaging enable accurate mine mapping, surveying, slope monitoring, and environmental assessment with reduced human risk.

### 3.8 Electrification and Sustainable Mining

Battery-electric equipment, hybrid vehicles, and renewable energy reduce emissions, fuel consumption, and operating costs while supporting sustainable mining.

### 3.9 Advanced Ore Processing Technologies

AI, automation, and sensor-based ore sorting improve mineral recovery, reduce energy use, and enhance resource efficiency.

### 3.10 Smart Tailings and Mine Closure Technologies

IoT sensors, satellite monitoring, and digital mine closure improve tailings safety, environmental monitoring, and sustainable land reclamation.4. Impacts of Emerging Technologies

## 4. Impacts of Emerging Technologies

### 4.1 Productivity Improvements

Emerging technologies improve equipment utilization, reduce downtime, increase production, optimize blasting, and lower fuel consumption, resulting in higher operational efficiency.

### 4.2 Safety Improvements

Automation, remote operations, collision avoidance, fatigue monitoring, and slope monitoring reduce accidents and enhance worker safety.

### 4.3 Environmental Sustainability

Modern technologies reduce carbon emissions, conserve water and energy, control dust, and minimize waste, supporting sustainable mining practices.


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### 4.4 Economic Benefits
Advanced technologies reduce operating and maintenance costs, extend equipment life, improve productivity, and increase return on investment.

## 5. Challenges and Limitations
### 5.1 Technical Challenges
The integration of AI, automation, IoT, and digital systems is often limited by poor connectivity, interoperability issues, and legacy mining infrastructure.

### 5.2 Economic Challenges
High capital investment, uncertain return on investment (ROI), and limited affordability hinder technology adoption, particularly in small and medium-sized mining operations.

### 5.3 Workforce Challenges
The implementation of advanced technologies requires skilled personnel, continuous training, and effective change management to support digital transformation.

### 5.4 Cybersecurity Challenges
Increasing digitalization exposes mining operations to cybersecurity threats, requiring robust data protection, secure communication networks, and reliable autonomous systems.

### 5.5 Regulatory Challenges
The rapid adoption of emerging technologies demands updated regulations, standardized guidelines, AI governance, and safety certification to ensure safe and compliant mining operations.

## 6. Policy and Governance Framework
The successful implementation of advanced surface mining technologies depends on strong policy and governance frameworks that promote responsible, safe, and sustainable mining practices. The International Council on Mining and Metals (ICMM) provides global principles for responsible mining, while Environmental, Social, and Governance (ESG) standards encourage sustainable environmental and social performance. The United Nations Sustainable Development Goals (SDGs) guide mining activities toward inclusive and sustainable development. Climate-smart mining supports the adoption of low-carbon technologies and efficient resource utilization. The Mining Policy Framework (MPF) promotes effective mineral resource governance and regulatory compliance. In addition, responsible sourcing ensures ethical mineral supply chains, tailings governance strengthens the safe management of mine waste, and local community participation improves stakeholder engagement, transparency, and long-term social acceptance of mining projects.

## 7. Analysis
The analysis of recent advances in surface mining technologies demonstrates a significant transformation of the mining industry from conventional, labor-intensive operations to highly automated, data-driven, and environmentally sustainable systems. The integration of digital technologies, artificial intelligence (AI), machine learning (ML), the Internet of Things (IoT), autonomous equipment, remote sensing, and drone-based monitoring has substantially improved operational efficiency while reducing safety risks and environmental impacts.

Autonomous haul trucks, drilling rigs, and dozers have significantly enhanced production efficiency by minimizing equipment downtime, improving cycle times, and reducing human errors. Real-time fleet management systems equipped with GPS and AI-based dispatch algorithms have optimized equipment utilization, reduced fuel consumption, and improved overall my productivity. Predictive maintenance technologies utilizing machine learning algorithms and sensor data have enabled condition-based maintenance, reducing unexpected equipment failures and maintenance costs.

Safety performance has improved considerably through the adoption of advanced monitoring systems, collision avoidance technologies, fatigue detection systems, wearable smart devices, and digital permit-to-work systems. Real-time slope stability monitoring using radar, LiDAR, satellite interferometry (InSAR), and geotechnical sensors enables early detection of potential failures, thereby minimizing the likelihood of catastrophic accidents. Furthermore, remote operation of mining equipment has significantly reduced worker exposure to hazardous environments.

Environmental sustainability has become a major focus in modern surface mining. Technologies such as electric and hybrid mining equipment, renewable energy integration, precision blasting, automated dust suppression systems, water recycling, carbon emission monitoring, and digital environmental management systems contribute substantially to reducing the environmental footprint of mining operations. Advanced blasting technologies have also minimized ground vibration, flyrock generation, and dust emissions while improving fragmentation quality.

The implementation of digital twins and integrated mine management platforms has enabled real-time simulation, optimization, and decision-making across the mining value chain. Cloud computing and big data analytics facilitate continuous monitoring of production, equipment performance, and environmental parameters, allowing mine managers to make informed operational decisions.

Despite these technological advancements, several challenges remain. High initial investment costs, inadequate digital infrastructure in developing countries, cybersecurity concerns, interoperability issues among different digital platforms, and the shortage of skilled personnel continue to limit the widespread adoption of smart mining technologies. Small and medium-scale mining operations, particularly in developing economies, often face financial and technical constraints in implementing advanced digital systems.


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Overall, the analysis indicates that the successful integration of innovative technologies not only enhances productivity and operational efficiency but also strengthens mine safety and environmental stewardship. Future mining operations are expected to become increasingly autonomous, intelligent, and sustainable through continuous technological innovation and digital transformation.

## 8. CONCLUSION

Recent advances in surface mining technologies have transformed mining operations by improving productivity, enhancing worker safety, and supporting environmental sustainability. Technologies such as AI, automation, digital twins, drones, and electrification have increased operational efficiency while reducing costs and environmental impacts. The integration of these innovations, supported by effective policies and skilled workforce development, will play a vital role in achieving safe, smart, and sustainable surface mining in the future.

## 9. Recommendations

Based on the findings of this review, surface mining industries should accelerate the adoption of advanced technologies such as artificial intelligence (AI), the Internet of Things (IoT), automation, autonomous equipment, and digital twin platforms to enhance operational efficiency, optimize resource utilization, enable real-time monitoring, and support data-driven decision-making. Continued investment in these digital technologies will improve production planning, equipment reliability, predictive maintenance, and overall mine productivity while reducing operational costs. From a safety perspective, mining companies should strengthen the implementation of intelligent safety systems, including collision avoidance systems (CAS), fatigue detection technologies, real-time environmental monitoring, smart personal protective equipment (PPE), and integrated mine surveillance systems to minimize workplace hazards and enhance worker protection. To achieve long-term sustainability, greater emphasis should be placed on the electrification of mining equipment, integration of renewable energy sources, energy-efficient mining practices, water recycling and reuse, and environmentally responsible waste management to reduce greenhouse gas emissions and conserve natural resources. Furthermore, collaboration among industry, academia, technology developers, and policymakers is essential to accelerate the development and deployment of innovative mining technologies while establishing appropriate regulatory frameworks and workforce training programs. Future research should focus on emerging technologies such as artificial intelligence, machine learning, robotics, edge computing, autonomous mining systems, digital twins, advanced sensing technologies, and integrated digital mining platforms to further improve innovation, safety, productivity, and sustainability in modern surface mining operations.

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