World Journal of Advanced Engineering Technology and Sciences
eISSN: 2582-8266
Cross Ref DOI: 10.30574/wjaets
Journal homepage: https://wjaets.com/

(Review Article)

Integration of Artificial Intelligence (AI) and Internet of Things (IoT) for Hazard Detection and Accident Prevention in Mining

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World Journal of Advanced Engineering Technology and Sciences, 2025, 17(02), 187-194

Publication history: Received on 29 September 2025; revised on 05 November 2025; accepted on 07 November 2025

Article DOI: https://doi.org/10.30574/wjaets.2025.17.2.1484

Abstract

Mining is among the world's most hazardous industries, where workers face constant exposure to risks such as rock falls, gas explosions, and equipment accidents. Despite advances in mechanization and safety management, fatal incidents persist due to the limitations of traditional monitoring and reactive safety systems. The advent of Artificial Intelligence (AI) and Internet of Things (IoT) has introduced new opportunities to enhance predictive, automated, and real-time safety solutions. This systematic review synthesizes current research on the integration of these technologies for hazard detection and accident prevention in mining. The study categorizes applications across geotechnical, environmental, and operational hazards and examines their technical mechanisms, benefits, and limitations. Findings reveal that AI enables data-driven hazard prediction; IoT ensures real-time environmental and equipment monitoring; and robotics extends operational safety through autonomous inspection and intervention. However, challenges including data scarcity, connectivity issues, and lack of standardization limit large-scale deployment. The review highlights future research directions such as digital twin development, edge computing, explainable AI, and human–robot collaboration as pathways toward intelligent, ethical, and sustainable mine safety systems.

Keywords: Artificial Intelligence (AI); Internet of Things (IOT); Mining Safety; Hazard Detection; Accident Prevention; Smart Mining

1. Introduction

Mining remains one of the most hazardous industries worldwide, accounting for a disproportionate number of occupational injuries and fatalities each year despite significant advances in safety management and regulatory enforcement. Underground and surface mining operations expose workers to multiple hazards including rock falls, ground collapses, gas explosions, equipment collisions, and environmental contamination. These hazards are often exacerbated by complex geological conditions, equipment failures, and human error. The persistence of accidents and near misses underscores the need for proactive, data-driven, and intelligent safety systems capable of detecting, predicting, and preventing hazardous events before they escalate into disasters.

Recent developments in Artificial Intelligence (AI), and the Internet of Things (IoT) have created new opportunities to revolutionize safety management in the mining sector. Robotics and autonomous systems are increasingly deployed to perform high-risk inspection, mapping, and sampling tasks in confined or unstable environments, thereby minimizing human exposure (Zhang et al., 2023). Similarly, AI—through machine learning, computer vision, and pattern recognition enables real-time hazard prediction, equipment fault diagnosis, and behavioral analysis of workers to

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enhance situational awareness (Tang et al, 2024). IoT networks further complement these technologies by integrating distributed sensor systems that monitor geotechnical, environmental, and operational parameters such as ground movement, gas concentration, temperature, and vibration, transmitting data for continuous analysis and early warning (Carri et al., 2021). Collectively, these technologies represent the foundation of Mining 4.0, which emphasizes automation, digitalization, and intelligent decision-making to achieve "Zero Harm" operations.

Despite growing interest, the integration of smart systems, AI, and IoT for hazard detection and accident prevention in mining remains fragmented. Most existing studies focus on isolated aspects—such as vision-based rock-fall detection, gas monitoring using sensor networks, or predictive maintenance for haul trucks—without a unified framework linking these innovations within the broader safety management ecosystem. Moreover, challenges related to data availability, sensor reliability, algorithm generalization, underground communication, and regulatory compliance hinder large-scale implementation. There is thus a pressing need for a systematic synthesis of existing research to identify trends, limitations, and future directions for the deployment of intelligent safety systems in mining operations.

This paper presents a systematic review of the current state of Artificial Intelligence, and Internet of Things technologies applied to hazard detection and accident prevention in mining. By consolidating interdisciplinary research across engineering, computer science, and mining domains, this review aims to provide a comprehensive understanding of how emerging intelligent technologies can transform mine safety management and support the global transition toward safer and more sustainable mining practices.

2. Overview of Hazards and Accidents in Mining

Mining is inherently associated with a wide range of occupational hazards due to its complex geological settings, confined workspaces, and the use of heavy machinery under extreme environmental conditions. Globally, mining contributes to a significant proportion of workplace fatalities, with underground operations accounting for the highest risk levels (Djanet Ey and Zakaria, 2025). In underground coal mining, methane explosions and roof collapses are predominant, while surface mining operations experience more vehicle collisions and slope failures (Zhang et al., 2021; Birkbeck,2021; Kolapo et al., 2022). The chain of causation typically involves early warning signs—such as micro seismic activity, vibration anomalies, or gas concentration fluctuations—that, if detected in real time, could enable preventive interventions. Although advancements in mechanization and safety management have reduced accident frequencies in developed regions, serious incidents such as roof falls, explosions, machinery collisions, and exposure to toxic gases continue to occur, particularly in developing mining economies (Onifade et al, 2023). Understanding the nature, sources, and classification of these hazards is fundamental for designing effective detection and prevention system.

2.1. Classification of Hazards in Mining

Mining hazards can be broadly categorized into geotechnical, environmental, mechanical, chemical, and human-related hazards, each posing distinct challenges to worker safety and operational continuity (Donoghues, 2002; Bagheri Naeini and Badri, 2024).

2.2. Geotechnical Hazards

These arise from ground instability, rock bursts, and roof or wall collapses. In underground mines, stress redistribution due to excavation can trigger roof falls or pillar failures, while in open-pit mines, slope instability and bench failures remain critical risks. Factors such as geological discontinuities, groundwater pressure, and inadequate support systems further exacerbate these risks (Li et al., 2025; Mishra and Rinne, 2015; Armah et al., 2025)

2.3. Environmental Hazards

Mines often contain hazardous atmospheres characterized by oxygen deficiency, the presence of methane, carbon monoxide, hydrogen sulfide, and suspended particulates. Poor ventilation can lead to gas accumulation, causing explosions or asphyxiation. (Sengupta, 2021). Temperature extremes, humidity, and dust exposure also affect worker health and sensor reliability.

2.4. Mechanical and Equipment-Related Hazards

Accidents involving mobile machinery—such as haul trucks, loaders, and drilling rigs—are a major source of fatalities. Collisions, rollovers, entanglement, and mechanical failures occur due to limited visibility, operator fatigue, and maintenance lapses (Souza et al., 2023). In underground settings, confined spaces and limited maneuverability heighten the risk of equipment-related injuries (Djanet Ey et al, 2025).

2.5. Chemical Hazards

Exposure to hazardous chemicals and reagents, including cyanide, mercury, and acids used in mineral processing, can cause severe health effects and environmental contamination. Improper storage or handling of explosives for blasting also presents a significant chemical hazard (Rebello et al., 2021)

2.6. Human and Organizational Factors

Many accidents stem from human error, inadequate training, noncompliance with safety procedures, and poor communication. Psychosocial stress, fatigue, and risk-taking behavior often amplify exposure to hazards, especially when safety culture and supervision are weak (Patyk and Nowak-Sendero ska, 2022)

3. Artificial Intelligence for Hazard Detection and Accident Prevention in Mining

Artificial Intelligence (AI) has emerged as a transformative technology in the mining industry, enabling predictive, adaptive, and autonomous safety management systems (Hyder et al., 2022). In the context of hazard detection and accident prevention, AI encompasses a range of computational methods—such as machine learning (ML), deep learning (DL), computer vision, and expert systems—that can analyze complex, multi-source data to identify hazardous conditions, predict failures, and recommend corrective actions in real time (Ali and Frimpong, 2020). The application of AI in mining safety aligns with the broader paradigm of Mining 4.0, where data-driven intelligence enhances decision-making and minimizes human exposure to risk.

3.1. Role and Function of AI in Mining Safety

3.1.1. AI systems in mining are primarily designed to perform three interrelated functions

- Hazard detection and classification, where algorithms identify anomalies or unsafe conditions using sensory or visual inputs;
- Risk prediction and decision support, where machine learning models forecast the probability of accidents based on operational or environmental parameters; and
- Autonomous control and response, where AI enables robotic systems to react or intervene to mitigate detected hazards (Javid et al., 2025; Hasan et al., 2025)
- These capabilities allow for a shift from traditional reactive safety approaches to predictive and preventive frameworks that continuously assess risk throughout the mining cycle.

4. Internet of Things (IoT) for Hazard Detection and Accident Prevention in Mining

The Internet of Things (IoT) has become a foundational pillar of smart mining, enabling real-time monitoring, data acquisition, and communication across distributed my environments. By connecting sensors, devices, equipment, and personnel through wireless networks, IoT facilitates continuous tracking of environmental, geotechnical, and operational parameters that directly influence safety performance. In the context of hazard detection and accident prevention, IoT transforms traditional mining operations into cyber-physical systems where information from the field is collected, analyzed, and acted upon autonomously or semi-autonomously (Molaei et al., 2020)

4.1. Role and Architecture of IoT in Mining Safety

The Internet of Things (IoT) plays a pivotal role in advancing mine safety by enabling continuous, real-time monitoring of environmental and operational conditions. Through a network of interconnected sensors, devices, and communication systems, IoT provides the foundation for data-driven hazard detection, predictive maintenance, and emergency response. Its integration into mining operations enhances situational awareness and reduces human exposure to hazardous environments by facilitating remote monitoring and automated centralist architectures in mining typically consist of three interconnected layers: the perception layer, the network layer, and the application layer (Alaba, 2024).

- The perception layer comprises sensors and data acquisition devices—such as gas detectors, vibration sensors, micro seismic monitors, and thermal cameras—responsible for collecting raw environmental and equipment data.
- The network layer enables data transmission through wireless communication technologies like ZigBee, Wi-Fi, Bluetooth Low Energy (BLE), LoRa, or 5G-based mesh networks. In underground mines, wireless sensor

networks (WSNs) and fiber-optic communication systems are often deployed to overcome signal attenuation and latency issues

- The application layer processes and visualizes the incoming data through AI and analytics platforms, providing real-time decision support for hazard prediction, worker tracking, and automated alarm generation.
- This multilayered framework allows IoT systems to integrate seamlessly with robotics, artificial intelligence, and cloud computing platforms, forming the technological backbone of Mining 4.0 safety management systems (Zhang et al., 2023; Aziz et al., 2020)

5. Limitations in Implementing Artificial Intelligence, and Internet of Things for Hazard Detection and Accident Prevention in Mining

Despite remarkable technological progress and promising research outcomes, the large-scale implementation of Artificial Intelligence (AI), and the Internet of Things (IoT), for hazard detection and accident prevention in mining remains constrained by several technical, economic, organizational, and regulatory challenges. The mining environment is characterized by harsh conditions, spatial confinement, and dynamic geological variability (Djanet Ey et al, 2025). This poses unique barriers that limit system performance, reliability, and scalability. Understanding these limitations is crucial for guiding future innovation and for developing sustainable frameworks for digital transformation in mine safety management.

5.1. Technical and Infrastructural Limitations

Mining operations expose sensors and devices to extreme humidity, dust, vibration, and temperature fluctuations, which degrade sensor accuracy and network reliability (Erie et al., 2024). Vision-based systems also struggle in low-light and dusty conditions. Reliable communication underground is another constraint; wireless signals face attenuation, and advanced systems such as LoRa or 5G require costly infrastructure. Power supply and maintenance are problematic as IoT nodes depend on batteries that are difficult to replace in remote areas. Furthermore, mining data are often incomplete or unstandardized, complicating AI model training and interoperability between devices (Aziz et al., 2020; Pramanik et al., 2024).

5.2. Algorithmic and Systemic Challenges

AI models face limited access to labeled hazard data, which reduces their generalization across different mine sites. Many deep-learning systems operate as “black boxes,” producing results without clear explanations, leading to skepticism among engineers and regulators. In addition, real-time processing remains difficult because of bandwidth limits and latency in cloud-based analytics (Matthew, 2025; Ajayi, 2025).

5.3. Economic and Organizational Barriers

Deploying AI and IoT systems involves high initial costs for hardware, software, and skilled personnel—an obstacle for smaller operations. Skill shortages and resistance to automation further slow adoption. Integrating new technologies with older, non-digital mining systems often requires expensive retrofitting or custom interfaces (Bhambri and Rani, 2023)

5.4. Regulatory, Ethical, and Security Challenges

The absence of clear certification standards for AI-based safety systems creates uncertainty about reliability and legal accountability. Expanding IoT connectivity also raises cybersecurity and privacy risks, as unauthorized access could disrupt monitoring networks. Moreover, increased automation introduces ethical concerns related to worker displacement and over-reliance on technology (Onu et al., 2025).

6. Future Prospects and Research Directions

The convergence of Artificial Intelligence (AI) and the Internet of Things (IoT) represents a transformative advancement in how the mining industry addresses hazard detection, accident prevention, and safety management. Although notable progress has been achieved, the realization of fully autonomous, intelligent, and integrated safety systems remains an evolving process. Future research should focus on improving technological robustness, interoperability, ethical governance, and human-centered system design to bridge the gap between innovation and practical field implementation.

6.1. Toward Intelligent and Autonomous Mine Safety Systems

Future mining operations are expected to evolve into adaptive and predictive ecosystems that can autonomously detect, assess, and respond to hazards in real time. The integration of AI and IoT will enable cyber-physical safety systems that continuously exchange information between digital and physical domains to enhance decision-making and efficiency (Shirokiya and Shrinking, 2023).

Developing autonomous hazard management frameworks that combine sensor data, predictive analytics, and automated response mechanisms remains a key research goal. Such systems will form closed-loop safety models capable of minimizing human exposure while maintaining operational reliability.

6.2. Integration with Digital Twins and Simulation Platforms

The use of digital twins—virtual replicas of mine environments—offers a major step forward for proactive hazard management. These systems, powered by real-time IoT data and AI algorithms, can simulate conditions such as ground deformation, gas buildup, or equipment malfunction before they occur (Don et al., 2025).Future work should focus on building multiscale digital twins that integrate both geotechnical and operational data, serving as decision-support tools for optimizing ventilation, equipment maintenance, and emergency response.

6.3. Advancements in Edge Computing and 6G Communication

Real-time hazard detection demands low latency and reliable connectivity, which traditional communication networks cannot always provide. Emerging edge computing architectures allow data to be processed locally at the sensor level, reducing dependence on cloud networks. The introduction of 6G communication will further enhance connectivity, supporting high-speed, low-power, and secure data transmission in deep or complex underground structures. These developments will enable seamless interaction between intelligent monitoring devices and centralized safety platforms (Hasan et al., 2025; Shen et al., 2025)

6.4. Explainable and Trustworthy Artificial Intelligence

To ensure widespread acceptance, AI systems must become more transparent and interpretable. Future studies should emphasize Explainable AI (XAI) that clarifies how models generate predictions and safety alerts. Incorporating ethical guidelines and uncertainty assessments will foster trust among engineers and regulators. Explainable models will also facilitate regulatory approval and responsible adoption in safety-critical operations (Uddin, 2025).

6.5. Human–Robot Collaboration and Augmented Safety

Rather than replacing human labor, the focus of intelligent technologies will be on human–machine collaboration. Smart robotic systems and wearable devices can assist workers in hazardous environments, while augmented reality (AR) and virtual reality (VR) will enhance training and situational awareness (Osei et al., 2025). These tools will allow miners to visualize real-time hazards and safety metrics, improving decision-making and reducing accident risks.

6.6. Sustainability and Circular Innovation

Future mining systems must align with sustainability and decarbonization goals. Research should prioritize low-power IoT devices, recyclable materials, and renewable-powered networks to reduce energy consumption and environmental footprints. AI and IoT data analytics can further optimize energy use, minimize idle equipment time, and support greenhouse gas reduction targets—ensuring that digital transformation complements environmental stewardship (Sutrisno et al., 2025).

6.7. Standardization, Policy, and Ethical Governance

The rapid adoption of intelligent technologies demands updated standards and governance frameworks. There is an urgent need for international guidelines defining safety validation, cybersecurity, and ethical use of AI and IoT systems. Governments, industry, and academia should collaborate to establish policy frameworks that promote responsible innovation, data sharing, and inclusive participation while protecting privacy and worker rights.There is the need for extensive research in data analytics, robotics, and AI for mining engineering to address the global skill gap.

7. Conclusion

The mining industry is undergoing a technological transformation driven primarily by Artificial Intelligence (AI) and the Internet of Things (IoT)—two pillars of the digital mining era that are redefining how hazards are detected, assessed, and mitigated. This review highlights how AI enables predictive safety analytics through machine learning, deep learning, and computer vision techniques capable of identifying unsafe conditions, forecasting geotechnical instabilities, and automating decision-making. Meanwhile, IoT provides the foundational network for continuous monitoring, integrating sensors and communication systems that capture and transmit real-time environmental and operational data to enhance situational awareness.

Despite these advances, the widespread application of AI and IoT in mining safety faces notable barriers, including harsh environmental conditions, limited underground connectivity, data scarcity, lack of interoperability, and regulatory uncertainties. Overcoming these limitations requires advances in edge computing, low-latency communication networks, and standardized data frameworks that enable reliable, scalable, and secure systems. Ethical considerations—particularly those concerning data privacy, accountability, and human oversight—must also be addressed to ensure responsible and transparent deployment.

Looking ahead, the integration of AI and IoT offers a clear path toward proactive, data-driven safety management that moves beyond traditional reactive approaches. When effectively combined, these technologies can provide continuous risk assessment, predictive hazard detection, and automated intervention—key enablers of the mining industry's vision for Zero Harm and sustainable operations. The future of mine safety will therefore depend not only on technological innovation but also on collaborative research, policy alignment, and workforce preparedness to ensure that intelligent systems remain reliable, ethical, and human-centered. By fostering interdisciplinary research, standardization, and digital literacy, the mining sector can move decisively toward a safer, smarter, and more sustainable future.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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