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

(Review Article)

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Examining the role of AI and machine learning in improving hazard detection and predictive analytics for accident prevention in mining operations

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World Journal of Advanced Engineering Technology and Sciences, 2025, 15(03), 640-646

Publication history: Received on 20 April 2025; revised on 28 May 2025; accepted on 31 May 2025

Article DOI: https://doi.org/10.30574/wjaets.2025.15.3.0874

Abstract

The paper critically reviews the application of Artificial Intelligence and Machine Learning in the mining sector to improve health and safety. Over the years, conventional safety measures have often involved reactive measures. Such traditional hazard detection methods are often disconnected, thus providing only limited safety improvements in the workplace. This paper looks at proactively monitoring health and safety by integrating machine learning and artificial intelligence into conventional systems to significantly improve decision-making, enhance safety, and drive continuous improvement. The review analyzes specific applications, including real-time hazard detection, predictive maintenance, worker behavior analysis, and environmental monitoring. Our findings demonstrate that AI/ML integration enables data-driven decision-making, automated risk assessment, and systematic safety improvements through continuous learning algorithms. This research contributes to the growing body of knowledge on technological innovation in mining safety and provides practical insights for industry stakeholders seeking to modernize their safety management systems.

Keywords: AI; Machine learning; Safety; Proactive; Models; Mining

1. Introduction

The mining industry is a crucial, complex, dynamic sector providing essential raw materials worldwide. The sector faces significant challenges in occupational health and safety, which is often characterized by diverse risks that can lead to serious injuries, illnesses, and economic losses [1]. There has been growing importance of safety analysis in high-risk industries influenced by various theoretical domains, leading to various frameworks to evaluate safety methods and ultimately offering guidance on accident prevention. However, the notable limitations of traditional hazard detection and prevention methods often rely on reactive and fragmented approaches, highlighting that experience alone does not ensure safety awareness and that one-time training interventions result in only short-term improvements in workplace safety [2]. To enhance the safety analysis of complex systems, we can integrate machine learning with traditional analysis to create a more adaptive and intelligent approach to detecting and understanding system anomalies [3].

Fundamentally, innovations around AI's pattern recognition and predictive capabilities can be used to create more intelligent, responsive, and preventative safety management systems that go beyond traditional reactive approaches. Ultimately, artificial intelligence, machine learning, and autonomous technologies have potential applications in the mining industry to improve productivity, safety, and efficiency through AI-driven hazard detection.

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1.1. Overview of AI/ML Technologies

Mining hazards are complex and multifaceted, requiring systematic classification and management that align with international standards of occupational health and safety (OHS) outcomes in the industry.

A study by Hyder et al., [4] explored the current and potential applications of artificial intelligence, machine learning, and autonomous technologies in the mining industry, highlighting their potential to improve productivity, safety, and efficiency. In a review that examines the transformative potential of Artificial Intelligence (AI) in critical mineral exploration, an illustration was made of how AI-based techniques can address challenges such as complex geological settings, declining ore grades, and the need for sustainable practices. It highlighted that leveraging machine learning, data analytics, and AI enables more efficient and accurate predictive modeling, allowing companies to utilize vast and previously underutilized datasets to improve exploration potential, decision-making, and project viability [5]. Autonomous technologies provide effective risk assessment as well as many economic profits such as cost reduction, continuous production, reducing laborer's exposure in dangerous environments, and enhanced protection [4]. The common Al approaches are computer vision, sensor networks, knowledge-based systems for decision-making, machine learning for data analysis, prediction, and evaluation, the Internet of Things - to enable communication of different devices or components connected to a network, and a data management system for storage, processing, and retrieval of data [6].

Despite promising advancements, the integration of AI in critical mineral exploration faces challenges including technical complexity, data requirements, and ethical and regulatory concerns, prompting ongoing research and development to refine AI algorithms and promote collaboration between geoscientists and AI experts.

1.2. AI in Hazard Detection

For instance, computer vision and AI techniques can be applied to improve safety monitoring in coal mines, which face complex underground environments with challenges like occlusion and high false detection rates in video monitoring. Experimental results indicated that AI-based image processing approach could achieve better information entropy (31.10% higher than previous methods), potentially enabling more effective detection and tracking of moving targets to enhance underground personnel safety [7]. Other research delved into a deep learning system using convolutional neural networks and transfer learning to autonomously detect roof fall hazards in mining environments, achieving 86.4% accuracy and demonstrating potential for complementing human expertise in geotechnical risk management [8]. Researchers have developed a deep learning-powered construction site safety management system using computer vision and building information modeling (BIM) to detect fall hazards and track worker and risk source locations, enabling automated and intelligent safety monitoring. Falling from height remains a critical safety issue in construction, with 75.1% of fall fatalities involving workers who did not use Personal Fall Arrest Systems (PFAS). To address this problem, research by Qi et al [10] developed an automated, deep-learning-based inspection method that can understand aerial work scenarios and check PPE usage by steeplejacks. The proposed system demonstrates reliability in detecting fall prevention measures, potentially improving safety supervision and reducing workplace accidents

1.3. Natural Language Processing (NLP) for analyzing incident reports

Studies developed confirm that language processing-based random forest models can be used to classify mining accident narratives with high accuracy, demonstrating the potential of machine learning in mine safety research and the existence of a consistent language for describing workplace accidents [11]. Rambabu & Rajive [12] in their study introduce MineBERT (Bidirectional Encoder Representations from Transformers), a novel BERT-based architecture specifically adapted for mining industry accident narrative classification, which demonstrates significant improvements over previous random forest models by reducing text ambiguity and achieving higher success rates across accident categories thus addressing challenges like homograph ambiguity and maintaining consistent performance metrics. In other studies, text mining and visualization framework using techniques like optimized term frequency-inverse document frequency algorithm (TF-IDF), word clouds, co-occurrence networks, and knowledge graphs to automatically extract and intuitively present key information from complex geological hazard documents, enabling faster and more efficient understanding of disaster reports [13].

2. Use Cases in Mining Operations - Monitoring and detecting hazardous conditions

Research by Guoquan et al. [14] describes a deep learning (DL) approach for analyzing gas sensor data in underground mining environments. The key aspects of their method include: Feature engineering using deep learning techniques, transforming time-series gas concentration data into recurrence plots (RPs), using machine vision methods to analyze these transformed images, analyzing sensor correlations based on sensor positions and time, predicting equipment failure and maintenance needs and worker tracking and behavior analysis for safety compliance. This research demonstrated a novel approach to understanding and predicting complex underground working conditions, thus enhancing mining safety. Ultimately, the integration of gas sensing technologies with IoT devices has led to real-time monitoring, data analytics, and smart automation [15]. For instance, algorithms are constantly being developed to improve gas detection in various settings equipped with the capabilities of real time data gathering to constantly monitor gas levels ensuring that gas leaks are immediately detected and reported to the relevant people using automated alerts. With a quick response time, actions can be taken immediately to prevent or reduce risks, accidents, or damage [16]. Additionally, harnessing the capabilities of camera imagery, machine learning, and gas sensors, has proven to elevate safety standards and reduction in incidents within coal mines [17]. Previous research by Sikora et al. [18] delved into systems that enable prediction of methane concentrations at the long fall face in coal mines which is able to monitor mining and ventilation processes and generate a forecast of the maximum methane concentrations in a specific region.

3. Technological Advancements

Technology presents other opportunities that have transformed the overall outlook of value addition in the mining industry. As highlighted by previous studies [19], various opportunities such as advanced geological modeling, the ability to integrate high-tech tools, enhancing operational efficiency, precision extraction, precision drilling, advanced sensor techniques, safety and risk management, and continuous improvement, holistically enable proactive decision-making, enhance safety, and drive continuous improvement. The interactions between the mining industry and technological advancements fall into the category of disruptive mining technologies as shown in Figure 1 below.

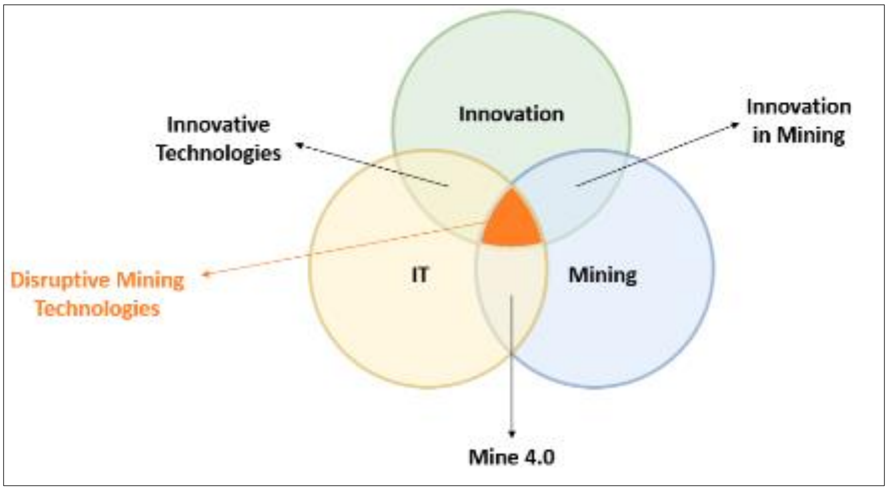

Figure 1 Disruptive Mining Technology Model

In a similar application of disruptive technology, research developed by Milka et al. [20] designed an integrated predictive approach driven by machine learning algorithms that trigger warnings when the AI model detects excessive noise levels or predicts an increased risk of (occupational noise-induced hearing loss) ONIHL. This was implemented to allow for continuous monitoring of noise levels.

Table 1 Performance of the machine learning algorithms [20]

Model	Average Training Accuracy	Average Testing Accuracy
Logistic regression	74.56	77.25
Support vector machines	86.00	99.12
Decision tree	92.25	99.89
Random Forest classifier	91.88	99.58

Table 2 Testing of the integrated system (Milka, 2024)

Distance of participant from machine (meters)	Priority level	Recommendation	Observation
60	low	None	No recommendation messages were received
50	low	None	No recommendation messages were received
40	low	Please wear your hearing protection	Successful SMS
30	Moderate	Hearing protection should be worn correctly	Successful SMS
20	Moderate	Hearing protection should be worn correctly	Successful SMS
10	Moderate	Hearing protection should be worn correctly	Successful SMS
5	High	Hearing protection should be worn correctly or step out of section	Successful
2	High	Hearing protection should be worn correctly or step out of section	Successful
1	High	Hearing protection should be worn correctly or step out of section	Successful
0.5	Extreme	Hearing protection should be worn correctly or step out of section Vibration	Successful SMS and Vibration

The ultimate goal of developing such models is to provide organizations with advanced predictive tools to improve health and safety practices, potentially preventing injuries and accidents proactively

4. Use of big data for improving ML model accuracy

Big Data Analytics involves processing and analyzing large volumes of data to uncover patterns, correlations, and insights that can drive decision-making and optimize operations [21]. The fast growth of digital technologies and systems has driven the generation of data in various industrial operations. As traditional data processing techniques are becoming insufficient to handle the huge amount of data continuously being produced, a transformative approach using Big Data analytics combined with advanced computational techniques, statistical methods, and machine learning algorithms has shown promise in extracting meaningful insights from vast and diverse datasets.

5. Benefits of AI and ML for Mining Safety

Integrating ML with accident databases and safety management systems can help identify accident precursors, improve safety interventions, and enhance prevention strategies. Additionally, combining ML with wearable computing and sensors, such as smart PPE and body cameras, enables predictive safety analytics to reduce workplace injuries and improve maintenance. Lastly, advanced tools like Deep Gaussian Processes (DGP) and Generative Adversarial Networks (GAN) offer potential for better uncertainty modeling and high-quality data generation to improve safety models [22].

Machine Learning can improve and automate how anomalous events can be detected and reported faster than before [23]. These technologies provide diverse economic benefits to the mining industry through cost reduction, productivity improvement, reduction in the exposure of workers to hazardous conditions, continuous production, and improved safety [4]. Other mining-related implementations of intelligent systems include fragment analysis of ores, intelligent ventilation, on-site mineral processing simplification, digital twinning, mineral exploration, mineral price forecasting, mining equipment selection, post-mining land reclamation and scheduling [24]. AI technologies are progressively becoming more versatile and have significant potential for transforming operational processes in mining enterprises.

Comprehensive implementation requires detailed information and continued investigation to ensure optimal neural network performance and integration [25].

The Predictive analytics that ML and AI provide in occupational health and safety further offer comprehensive benefits like proactive risk prevention, improved operational efficiency, financial savings, regulatory compliance, enhanced workplace safety, and increased employee well-being and productivity.

Table 3 Salient Components of Predictive Analysis and Their Impact on Occupational Health and Safety (Vyom, 2024)

Key Component	Description	Impact on Occupational Health and Safety
Data Collection	Gathering relevant safety data (Incident reports, safety audits, sensors, etc.)	Ensures comprehensive information is available for risk analysis, helps in identifying trends and emerging hazards.
Data Management & Preparation	Organizing, storing, and cleaning data for analysis	Enhances data accuracy and reliability, ensures the proper integration of diverse data sources for better predictive outcomes
Analytical Methods	Statistical techniques (e.g., regression, time-series analysis) and machine learning algorithms	Identifies relationships between variables, detects trends, and predicts potential risks, leading to proactive safety measures
Predictive Modelling & Risk Assessment	Developing models to forecast future safety risks	Enables proactive risk management by identifying where and when accidents are likely to happen, facilitating targeted interventions and safety strategies
Interpretation & Implementation	Turning predictive insights into actionable safety strategies	Allows organizations to implement preventive measures based on predictions, optimize safety protocols, and reduce incidents
Training & Communication	Educating employees about interpreting insights and fostering participation in preventive measures	Promotes a culture and safety, empowering employees to actively engage in hazard prevention, increasing the overall effectiveness of safety initiatives.

Challenges and Limitations

The implementation of new technologies in disaster prevention faces multifaceted challenges such as personnel training requirements, data privacy concerns, AI reliability issues, high technology costs, particularly affecting developing regions, and the need for enhanced public education and understanding [26].

6. Conclusion

The integration of Artificial Intelligence and Machine Learning technologies in mining operations represents a significant advancement in transforming traditional reactive safety approaches into proactive, data-driven solutions. Through various applications such as computer vision, natural language processing, sensor networks, and predictive analytics, these technologies have demonstrated substantial improvements in hazard detection, risk assessment, and accident prevention. The implementation of AI-driven systems has shown promising results in areas such as gas detection, noise monitoring, roof fall prevention, and worker safety compliance, with documented improvements in accuracy, efficiency, and response times.

However, while the potential benefits are substantial, the successful implementation of AI and ML in mining safety faces several challenges that need to be addressed. These include data quality and privacy concerns, technological constraints, implementation barriers, and regulatory considerations. Moving forward, the mining industry must focus on developing more robust and adaptable models, establishing standardized datasets, enhancing real-time monitoring capabilities, and fostering collaboration between AI specialists and domain experts. By addressing these challenges while maintaining a commitment to ethical and transparent AI systems, the mining sector can fully harness these technologies to create safer, more efficient operations that protect workers' well-being while optimizing productivity.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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