AI and Automation in Mining: A Comprehensive Systematic Review of Efficiency and Sustainability

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Abstract
Mining plays a pivotal role in driving the global economy, serving as essential raw materials for a wide range of industries. However, the mining sector is currently confronted with numerous critical challenges, including minimizing environmental degradation, improving productivity, ensuring efficient resource utilization, and safeguarding the health and safety of workers. Although traditional mining practices have significantly contributed to industrial development, they continue to raise concerns related to environmental sustainability, depletion of natural resources, and occupational hazards. In this context, the integration of Automation and Artificial Intelligence (AI) has emerged as a transformative solution for the modern mining industry. This paper examines various automation and AI-driven technologies being implemented across the mining sector and explores the extent to which these advanced technologies have been adopted to enhance operational efficiency, sustainability, and worker safety.

Keywords: Automation in Mining, AI, Intelligent Mining Solutions, Sustainable Practices

Introduction

Mining plays a crucial role as a key sector of world economies as it ensures supply of essential raw materials required for the development of infrastructures, creation of energy, and manufacturing industries (Jovanović 2023; Franken 2022). Despite the importance of the enterprise, it experiences various complex problems which demand flexible and innovative approaches towards resolving them. According to recent studies, there are four aspects related to the complexity of the problems: economic, environmental, operational, and social (Amegboleza, 2026; Joseph, 2025). The first one is connected with problems of unstable prices of products, increase in extraction costs owing to deep and complex ores as well as high level of competition among companies at an international level (Chatterjee 2025; Amegboleza, 2026). These factors put pressure on companies' profits which require continuous optimization. Environmental problems create additional difficulties as mining enterprises cause substantial damage to ecosystems through pollution of air and water resources, excessive use of water, deforestation, and loss of biodiversity (Joseph, 2025; Teku, 2025; Mishra, 2023). Mining processes are inherently complex due to being carried out in remote and dangerous areas, which pose numerous hazards for the miners (Obosu, 2025; El-Helaly, 2024; Rojas, 2025). Issues such as enhancing productivity, ensuring safety, and maintaining efficiency are vital aspects (Corrigan, 2024; Lang, 2024). Furthermore, the social problems that emerge as a result of the impacts of the mining operations on the community include those related to ownership of land, displacement, socio-economic inequality, and revenue distribution. It is imperative, therefore, to have stakeholder involvement as well as sustainable development in order to deal with such problems (Sydd 2022; Teku, 2025; Horn 2025). Such overlapping issues have become even more apparent owing to increased global demand for minerals and stricter environmental regulations (Faradonbeh 2026; Franken 2022). There is, therefore, an urgent need for developing sustainable mining practices. This transformation can be seen through the increase in scholarly work regarding sustainable mining, particularly focusing on automation and artificial intelligence in various stages of mining (Faradonbeh 2026; Obosu 2025). Bibliometric analysis shows an evident rise in research on automation, artificial intelligence, digital twins, and IoT in mining since 2017, indicating a fast shift to digitalization and smart technologies. Given this background, the application of transformative technologies, namely, automation and AI, has emerged as one of the key approaches to addressing the challenges faced in industries in question (Corrigan 2024; Chen 2024; Rashid 2024).

There is a number of sound arguments for utilizing automation and artificial intelligence within mining organizations. These technologies help streamline processes, reduce downtime, increase productivity, and decrease operational costs (Lang, 2024; Obosu 2025; Rojas 2025). In addition to that, it is possible to increase the effectiveness of resource management and utilization through improved accuracy of extraction, resulting in decreased losses due to inefficient material consumption (Chatterjee 2025; Pandey 2026). Another key advantage provided by those innovations relates to increased safety of workplaces owing to reduced employee exposure to

dangerous conditions and risk prediction based on predictive analytics (El-Helaly 2024; Obosu 2025; Censi 2025). Further, through automation and artificial intelligence, there are enhanced environmental performances as a result of waste minimization, low emission production, resource management, and regular compliance verification (Joseph, 2025; Corrigan 2024; Chen 2024). Finally, advanced data analytics powered by artificial intelligence can be employed for decision-making and planning purposes, thus assisting mining entities to effectively handle their complicated processes (Rojas 2025; Pandey 2026; Censi 2025). The purpose of this literature review is to comprehensively review the recent trends in automation technology and artificial intelligence in the mining sector, focusing particularly on the ways through which automation technologies and artificial intelligence have improved the mining process in terms of efficiency, sustainability, and worker health. The applications of automation technologies and artificial intelligence are carefully evaluated; the challenges encountered by firms in implementing them are discussed; and the problems that should be considered in the future to enhance their acceptance are identified. Both strengths and weaknesses of this emerging trend in the mining sector are analyzed.

AI and Automation in Mining

The difference between automation and artificial intelligence in mining needs an elaboration on the term "automation." According to Kaber (2018) and Kokkinis et al. (2024), automation is the use of technology to conduct activities without human intervention or with minimal human interaction. In the mining industry, automation takes place through a variety of levels – from technologies that assist operators with drilling and loading activities to fully automated systems, such as haulage activities. It includes robotization for inspection and maintenance tasks along with automated control systems for ventilation and material handling processes (Firoozi 2024; Cacciuttolo 2023; Kokkinis 2024). On the other hand, artificial intelligence relates to the development of computers capable of imitating human thought processes (Peres 2020; Ngubane, 2026; Hasan 2025). Artificial intelligence includes various methods in the mining field. For example, machine learning makes it possible for computers to analyze information, identify patterns, and increase efficiency in time. Therefore, this method of artificial intelligence works particularly well in situations like predictive maintenance and resource distribution (Dyczko, 2023; Fattahi 2024; El Bazi 2023; Bertoni 2022; Jan et. Al., 2023; Ajayi 2025). Neural network, which has been modeled after the human brain, is good at detecting complicated patterns, which include the assessment of the grade of the ore through image analysis and predicting the characteristics of the coal (Dyczko 2023). Additionally, big data analytics plays an important role in the application of AI in the mining sector because the industry generates massive amounts of data from sensors, machines, geological surveys, and Internet of Things. An appropriate analysis of such data leads to better decision making (Javaid 2022; Cao 2023; Onu 2025). AI applications have been used in numerous areas in the mining process including improving drilling and blasting processes, predicting equipment malfunctioning, assessing the environment, ensuring safety through autonomous systems, and fostering sustainable practices in the mining process (Fattahi 2024; Dehkordi 2024; Abdellah 2022; Tang 2024). New findings and evaluations highlight the need for speedy adoption of such new technologies to boost performance, safety, and sustainability. Future technologies under consideration are the ones such as digital twin, 5G infrastructure, and Industry 4.0. (Obosu, 2025; Ghosh, 2023).

Automation: Safety and Efficiency

Automation has increasingly spread within various stages of mining activities such as exploration, extraction, transportation, and processing during recent decades (Pouresmaieli 2023). These innovations have brought many advantages in increasing productivity, enhancing the safety of the processes, and generally boosting the level of performance, bringing mining from manual operations into more advanced technology-based stages. One of the most prominent advantages of automation is decreasing costs associated with labor and ensuring higher safety in the workplace. Automation lowers accidents' frequencies and limits human interaction with dangerous processes, minimizing risks of injury and harm (Gaber 2021).

An important development in the mining industry includes the application of Autonomous Haulage Systems (AHS) for haulage purposes (Long 2024). As noted before, these systems make use of current sensors, GPS, and artificial intelligence algorithms that have become increasingly common in underground and surface mining. For example, the Autonomous Haulage System (AHS) is more efficient since it can work around the clock without stopping and through optimal routing over challenging terrain to eliminate delays. It is evident that automatic haulage trucks outperform manual trucks in many ways, hence making them more cost-effective in mining operations (Cacciuttolo 2023). Table 1 summarizes the analysis of automation technology used in mining operations in terms of their function, features, strengths, and weaknesses.

Table 1. Overview of Mining Automation Technologies

Application Area	Technologies Used	Benefits
Autonomous Haulage Systems	GPS, sensors, AI algorithms	Enhanced productivity via uninterrupted operations Decreased operating expenditure Enhanced safety
Automated Drilling and Blasting	Precision control systems, robotics	Enhanced precision in blasting operations Minimized over-excavation Reduced ecological footprint
Robotic Systems	Advanced vision systems, AI-powered sensors	Improved inspection skills Minimized human exposure to risks Reduced maintenance expenses

Figure 1 demonstrates the comparison between the performance indicators of mining operations that are either automated or traditional through important operational parameters. These improvements include notable gains in terms of safety, effectiveness, and optimization after the application of automation technology (Cacciuttolo 2023; Firoozi 2024).

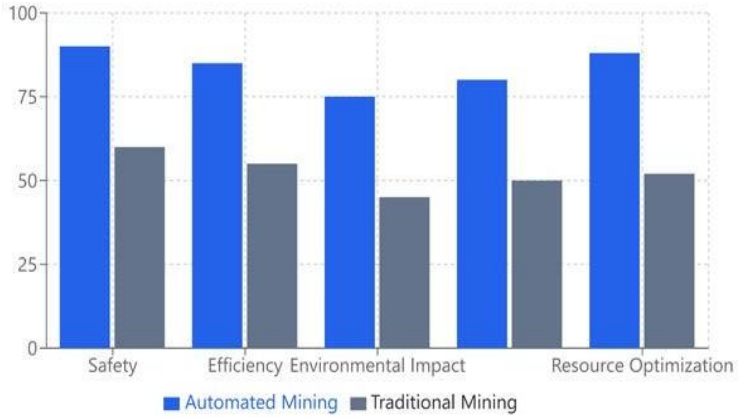


Figure 1. Comparative examination of automated and conventional mining operations across five principal performance metrices

In mining, there have been notable advancements towards automation in drilling and blasting activities alongside autonomous haulage solutions (Long 2024). This trend has been developed to increase efficiency in basic processes such as drilling and blasting, whose productivity plays a pivotal role in determining overall productivity. The benefits of automation in mining include increased accuracy, safety by preventing hazards related to employee risks, and eliminating errors that would arise due to the manual approach. According to research findings, automating blasting has been found to increase accuracy in blasting activities, thereby lessening the ecological footprint of the process (Cacciuttolo 2023; Fattahi 2024; Nikkhah 2022). The application of robots in mining has greatly improved the performance of processes such as inspection, maintenance, and repairs. Robots with advanced vision and artificial intelligence sensors perform admirably in hazardous environments, hence reducing the risk of injury and exposure to human workers. Apart from enhancing safety, robots are beneficial in improving operations by reducing downtime and maintenance costs (Szrek 2022; Topolsky 2022). However, despite all the apparent benefits associated with automation in mining, the process of automating mining operations is faced with a number of challenges as well. The first important challenge relates to the high capital cost involved in implementing automation technologies that may be quite hard to raise by small mining enterprises (Wang 2022). Additionally, automation technologies require skilled labor and involve additional costs related to personnel development and skill improvement (Pouresmaieli 2023). The implementation of automation technologies can take place only under conditions of reliable networking infrastructure that presents a challenge in remote areas where mining operations are being conducted.

AI in Mining: Sustainability and Resource Management

Machine learning and deep learning advanced technologies becoming increasingly necessary for improving mining processes (Jafari 2022; Ofori-

Boateng 2024). They allow mining companies to analyze data efficiently and utilize them effectively as collected from various sources, including sensors, machinery, and geological surveys. As a result, enterprises are able to make more informed decisions that help improve mining efficiency and create more environmentally-friendly operations. Figure 2 illustrates how different AI technologies interact with each other and helps in understanding their implementation and application in the mining industry (Jan 2023; Javaid 2022). AI technologies are making significant progress in predictive maintenance in the mining industry as complex algorithms allow analyzing sensor data to identify potential system failures before a piece of equipment fails (Keleko 2022). It reduces operating costs due to increased machinery longevity and minimized downtime. Furthermore, such an approach would aid in enhancing the overall efficiency of various mining activities and facilitate environmental sustainability. The applications of AI in the mining industry are listed in Table 2 below, alongside their benefits.



Figure 2. Mind map for AI applications in mining operations

Table 2. Utilization of Artificial Intelligence in Mining: Functional Evaluation and Impact Analysis

AI Application	Primary Function	Environmental Benefits
Predictive Maintenance	Analyze equipment sensor data to predict failures	- Reduced waste from equipment failures - Optimized resource usage
Resource Management	Analyze geological data for optimal extraction	- Minimized waste generation - Reduced environmental footprint
Environmental Monitoring	Real-time analysis of environmental parameters	Better pollution control Improved water management - Reduced ecological impact

AI has been vital in recent times in enhancing resource management and ore extraction in mining facilities (Noriega 2022). AI has allowed the prediction of high-value ore deposits based on geologic data, thereby ensuring that mines are run efficiently and minimize resource waste. This aspect contributes towards enhancing resource efficiency, protecting the environment, and lowering operating costs. Additionally, AI is essential in the segregation process whereby ores are sorted in order to maximize the extraction process while segregating wastages. With such technological advancements, there are significant reductions in wastage production, hence minimizing adverse environmental effects (Cacciuttolo 2023). AI is also vital in environmental monitoring based on the evaluation of real-time data regarding pollution in the form of air, water, and noise pollution (Jiang 2022). The above attribute makes it relatively easy for mining organizations to adhere to environmental regulations. Another vital application of AI in the mining industry is its contributions towards enhanced energy efficiency, thereby reducing greenhouse gas emissions (Ahmad 2022). However, although there are many benefits, some challenges exist concerning the implementation of AI technology in mining activities. First, there must be ample data to come up with an efficient AI system, and this may not always be easy to get during mining operations. The

sophistication of AI technology requires specialized expertise to ensure proper algorithm development, and this can be a big challenge for many firms. Lastly, there are ethical concerns like the security of data and removing bias from the algorithms (Dyczko 2023).

AI in Mining: Supporting Technologies

Use of AI and automation technologies in mining comes as a result of the availability of technology that can gather, analyze, transmit, and manage data. The technology mentioned above constitutes the key components of an intelligent mining system of today. Advanced sensing technologies are critical to collect information needed for AI and automation. Advanced sensing technologies like satellite imagery and LiDAR have proved to be instrumental in the process of mineral exploration because they enable mapping and locating metal deposits (Murray 2022). They provide environmental monitoring by detecting vegetation, water, and land use change. When it comes to mining, there are various types of sensors which perform different functions. Motion sensors and vibration sensors help to monitor the performance of mining equipment, detect problems, and forecast future problems (Madahana 2022). It is essential to highlight that gas sensors have proved to be crucial in underground mining operations due to their ability to analyze air quality and detect dangerous gases. Furthermore, pressure and temperature sensors offer essential information for process optimization, whereas proximity sensors enhance safety since they detect other things or humans around, thus minimizing the risks of accidents.

Robotics enhances automation in the industry with the help of various applications. Firstly, mobile robots transport material, manage dangerous materials, and assess difficult or risky areas. Secondly, robotic technology at processing plants performs activities including sorting, crushing, and grinding. Thirdly, aerial robots, otherwise called drones, become increasingly common in mine inspections and structure analysis; this helps save money and time (Stothard 2023). Subterranean robots designed for harsh conditions enable drilling, exploration, and emergency operations to be performed. With the assistance of AI and computer vision, the robots can work independently, for example, analyze tunnel walls without any human supervision. Cloud computing is indispensable in providing flexible infrastructure for storing and managing huge volumes of data about mining (Mistry 2024). It eliminates the need for expensive data centers within the mining site and allows mining organizations to run complicated AI algorithms through high-powered computing facilities. Cloud technology supports remote data retrieval, allowing for real-time tracking and control of the process from distant locations. Additionally, it boosts data management, security, and collaboration while delivering scalable solutions at an affordable cost (Ionescu & Diaconita, 2023). VR and AR technologies significantly contribute to enhancing training, designing, and maintaining mining operations. The virtual reality technology is beneficial in creating the environment that would be used for training whereby the employees would acquire skills in handling the equipment in addition to emergency procedures in a secure and safe environment. The augmented reality technology ensures that the operation on the construction site becomes easy as the technology uses overlays of computerized information within the physical environment hence making operations effective (Cacciuttolo 2023; Haleem 2021). The two technologies help with design and maintenance of the equipment. Reliable communication channels are important for ensuring continuous connection during the mining process. Fast communication technologies, including 5G, Wi-Fi, and satellite networks, help transmit data instantly and operate machinery remotely (Cao 2023). The need for data management systems becomes important due to the immense amounts of data created during mining processes. Through data management systems, the use of tools that allow for the collection, storage, organization, and analysis of data for effective data presentation is achieved (Himeur 2023). Data management systems provide precise information at the right time, which helps make better decisions through informed analysis. IoT technology becomes essential due to the interconnectedness of many technologies. It forms a networked framework in which devices, sensors, and systems are easily integrated in the mining process (Aguirre-Jofré 2021; Siahkouhi 2024). IoT supports data gathering in real-time, interconnection of devices, remote operation, data-based decision making, and automation through communication among machines.

Business Model Innovation and Digital Transformation

The mining industry is seeing significant digital change propelled by the integration of automation and artificial intelligence technology. The change is not only about improving operational efficiency; it also leads to changes in business models and decision-making strategies (Abdellah 2022; Zhironkina 2023). One of the major innovations that can be mentioned in this context is digital twins, that is creating virtual models of mining machinery and processes. Digital twin technology helps operators monitor information, simulate various scenarios and improve their performance. Using digital twins makes it possible for companies to receive more advanced information about equipment performance, efficiency of various processes and general working conditions in the mines (El Bazi 2023; Plavšić & Mišković, 2024). Increasing availability of data provided by sensors and autonomous equipment and other digital means made data-based decision-making even more popular in mining. Collecting data from different sources will help companies increase their productivity, reduce costs, and reach sustainability goals. As a result, data-driven approaches contribute to greater productivity,

reduction of downtime, and more efficient utilization of resources, thus promoting economic and ecological sustainability (Parida 2019).

Moreover, embracing digital technologies calls for adopting novel business models (Bertoni 2022). Traditional approaches revolving around the extraction of minerals have been increasingly replaced with service-oriented strategies that focus on performance, sustainability, and stakeholder engagement. Increasingly common are performance-based contracts whereby rewards depend on achieving certain efficiency and sustainability goals. These approaches encourage accountability and align financial outcomes with ecological and societal benefits (Parida 2019). The adoption of a new paradigm based on digital and service-oriented solutions demands significant investments in infrastructure, human capital, and corporate culture. Mining enterprises need to remain agile and proactive in adapting their business model to make full use of the potential offered by digitalization. Solving these challenges entails collaboration between industry stakeholders, government agencies, and scholars to develop frameworks that will ensure proper and ethical use of digital technology.

Overall Environmental Impact & Sustainability

There is a huge number of environmental impacts within the mining industry, and addressing these impacts has become a matter of great importance. One such impact includes water pollution, ecosystem degradation, and greenhouse gases, which have long-lasting implications on the surrounding areas and populations (Adeniyi 2022; Rentier and Cammeraat, 2022; Vinayagam 2024). Considering the challenges posed, there is an increasing requirement for adopting sustainable mining processes. Some recent innovations within the field include automation and artificial intelligence (AI), which could help in reducing any negative impacts through efficient use of resources, reduced waste generation, and greater energy efficiency. There is great proficiency in using AI systems to manage energy and water resources. Using real-time sensor information, these can accurately forecast water usage and conserve water resources. It becomes especially relevant for regions that suffer from water scarcity and contamination due to mining operations. In addition, AI helps in conserving energy by predicting the amount of energy required during operation and making suitable modifications in the industrial process. Increased energy efficiency leads to reduced CO2 emissions and a decreased reliance on fossil fuels (Cacciuttolo 2023). As can be seen in Fig. 3, the radar map analysis of automated vs. conventional mining shows an improved environmental impact in many sustainability metrics (Nwaila 2022; Onifade 2024; Pouresmaieli 2023).

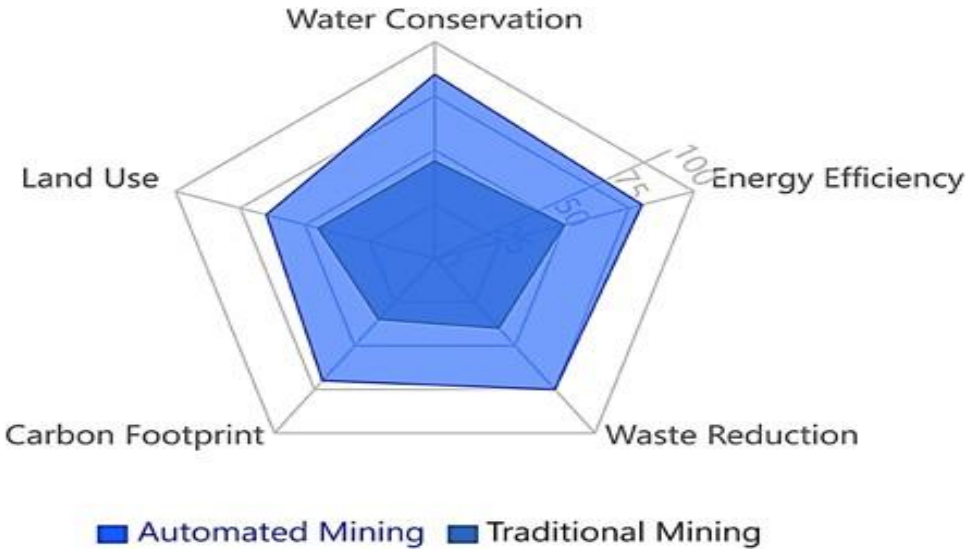


Figure 3. Radar map juxtaposing sustainability performance measures of automated vs conventional mining operations across five principal environmental variables. Values are standardized on a 100-point scale, with higher values signifying superior environmental performance.

Integration of renewable energy into mining processes is increasingly becoming common, thus making it a prominent trend in the industry. This is because artificial intelligence is required in forecasting the amount of energy that will be produced from natural sources such as wind and solar energy and altering the mining processes accordingly (Nepsha 2023; Vergara-Zambrano 2022). As a result, miners will have less use for fossil fuels and this improves their sustainability performance. Additionally, AI plays an important role in the management of tailing dams due to the environmental risks associated with these systems. Through analyzing data related to the conditions of the dams, any potential dangers can be predicted and avoided.

Conclusion

The use of automation and artificial intelligence (AI)

in mining operations offers a substantial chance to revolutionize the sector by improving productivity, environmental sustainability, and worker safety. Technologies like autonomous cars, robotic systems, and automated drilling equipment are optimizing operations, decreasing expenses, and enhancing safety standards. Moreover, AI provides robust functionalities for enhancing resource management, allowing predictive maintenance, and supporting real-time environmental monitoring. Notwithstanding these benefits, the implementation of these technologies presents several problems. Substantial initial capital expenditures, the need for a technologically proficient staff, and challenges in harmonizing disparate digital systems persist as significant obstacles. Moreover, significant research deficiencies exist concerning data quality, system scalability, interoperability, and the wider societal ramifications of automation in mining.

To fully harness the promise of automation and AI, more research is necessary to tackle these difficulties, provide economical solutions for smaller mining enterprises, and build definitive legal frameworks for responsible application. As the mining sector progresses swiftly, cooperation among industry participants, governmental bodies, and academics is crucial to foster innovation and guarantee sustainable practices. Ultimately, while initial hurdles may occur, the use of these technologies may empower mining businesses to function more responsibly—reducing environmental effect, protecting workers, and aiding neighboring communities while ensuring economic sustainability.

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