ISSN 1840-4855
e-ISSN 2233-0046

Original scientific article
http://dx.doi.org/10.70102/afts.2025.1834.1196

QUANTIFYING THE IMPACT OF ROBOTICS AND AUTOMATION ON SAFETY AND OPERATIONAL PERFORMANCE IN MODERN MINING SYSTEMS

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Received: October 11, 2025; Revised: November 14, 2025; Accepted: December 15, 2025; Published: December 30, 2025

SUMMARY

The aim of the research is to assess the applicability of robotics and automation technologies to enhance safety performance and operational efficiency in mining operations in surface, underground, and coal mining settings. A mixed-methods and systematic approach was embraced, which involved the secondary data through peer-reviewed publications, industrial reporting, and reported mining cases. The applicability of autonomous haulage systems, robotic drilling and inspection systems, UAVs, patrol robots, swarm robotics, and intelligent sensor networks was evaluated based on the main safety and efficiency indicators. A coherent analytical system was established in order to compare the correlation of accident minimization, reduction of exposure to workers, productivity improvement, and equipment functionality in various mining conditions. The findings reveal that there was a great safety enhancement, and the rates of reduction of accidents are 39.1% in surface mining, 51.4% in underground mining, and 48.0% in coal mining. In underground operations, exposure of workers to hazardous areas was reduced by up to 58.9%. There was also a significant improvement in the operational efficiency, whereby there was an increment of equipment use by 30.7%, productivity output by 31.6%, a reduction in the cycle time by 30.8%, and a decline in the unplanned downtime by 45.3%. The greatest combined benefit was seen in underground mining based on the integrated Safety -Efficiency Index (SEI = 17.6). The results prove that robotics and automation allow improving safety and efficiency simultaneously, especially in the high-risk mining areas, which facilitates the shift toward safer and more sustainable mining processes.

Key words: *automation, mining safety, operational efficiency, robotics, smart mining.*

INTRODUCTION

The international mining sector plays a critical role in providing raw materials that are vital in energy, infrastructure, and industrial developments [1]. Nevertheless, mining is a volatile activity in that the geological factors are unstable, the working conditions are restricted, the workers are subjected to toxic fumes, and the employment of heavy machinery is involved. The mining technique that has been used over the years depends greatly on handwork and man-operated machines, which considerably raise the chances of accidents, work-related injuries, and fatalities [2]. In the past few years, the breakthrough in robotics, automation, artificial intelligence, and sensor technologies has made it possible to come up with autonomous and semi-autonomous mining systems. These technologies provide the possibilities to increase the efficiency of operations, the level of situational awareness, and reduce human exposures to hazardous conditions, and provide cost-effective and sustainable mining activities [3][4].

The major aim of the study is to examine how robotics and automation technologies can enhance safety and operational efficiency in mining work. In particular, the project will help accomplish the following objectives: assessing the role of autonomous equipment, robotic platforms, and intelligent monitoring platforms in minimizing accidents, improving productivity, making decisions in real-time, and optimizing the use of resources in the surface and underground mines [5][6].

Although the use of automation in mining is increasingly becoming common, the available literature is mainly on a technology-by-technology basis or a case study with minimal incorporation of safety performance measures and indicators of operational efficiency [10]. No universal models have been established that can be used to measure the overall effect of robotics and automation on the safety of humans and the overall productivity of the system. The hypothesis of this study will be that the synergistic implementation of robotic systems and automated control structures will greatly minimize the level of safety risks and, at the same time, increase the efficiency of operations relative to the traditional mining operations [13][17].

This study makes the following key contributions:

- Gives a systematic review of robotic and automation technology that is used in mining on the surface and underground.
- Designs a combined analytical model between safety performance measurements and operational efficiency measurements.
- Asserts whether autonomous and semi-autonomous systems are effective in minimizing human exposure to high-risk mining conditions.
- Determines the implementation issues, technology constraints, and research prospects of the intelligent mining systems.

This paper has been organized in such a manner that it systematically presents how robotics and automation have influenced the safety and operational performance in the mining environment. Section 1 provides the background of the research, objectives, hypothesis, and major contributions. Section 2 gives a detailed review of the literature concerning robotic, automated, and intelligent mining technologies. Section 3 outlines the materials and methods, such as the source of data, safety and efficiency measures, and the analytical framework. Section 4 summarizes and describes the findings with the help of quantitative tables and figures. Section 5 explains the discussion of findings with respect to existing studies and practice in the industry. Section 6 is the conclusion of the article with a summary of major outcomes, implications, and future research directions.

LITERATURE REVIEW

Recent developments in robotics and automation have also brought about a great change in the mining process, with a high focus on enhancing the safety and productivity of operations. Obosu and Frimpong [1] give a detailed rundown of the changing future of the mining industry, and how autonomous machinery, robotics, and online platforms are transforming the mining operations of the past. Their research highlights that the automation-based mining ecosystems can significantly decrease human exposure to risky environments and ensure the maintenance of sustainable production goals.

Some of the researchers have focused on equipment- and operation-level automation. Long et al. [2] have conducted a review of automated drilling, hauling, and loading systems development and were able to identify a significant increase in productivity, fuel efficiency, and equipment usage. In the same line, Du et al. [3] enumerated robotic automation of industries in the mining sector, and they indicated that robotic manipulators, robotic inspection, and autonomous vehicles have moved past research prototypes to commercial models. Nevertheless, they too opined that there were some problems associated with system integration and reliability in the harsh mining environment.

Key indicators that were used to determine safety performance include the decline in the frequency of accidents, the level of exposure of the workers to dangerous areas, the efficiency of the hazard detection system, and the reliability of the real-time monitoring systems. Reported implementation data was compared and contrasted to determine the risk reduction of geotechnical instability, toxic gases, equipment-collision, and human error mitigation of robotic and automated systems. To determine the safety performance differentials, a comparative analysis was done between the traditional mining activities and automated systems.

Modern mining transformation is based on digitalization and smart technologies. Onifade et al. [5] noted that technical innovations, including automation, real-time observation, and decision support, are very instrumental in enhancing the safety of operations. Onifade et al. [18] talked about the difficulties in digital technology application to mining, such as the high cost of capital, lack of skills of the labor force, and cybersecurity risk in a related study. Some of these barriers would be overcome through low-cost sensing solutions suggested by Cacciuttolo et al. [16] to scale safety and sustainability monitoring.

New paradigms in robotics have also been addressed. Tan et al. [7] tested swarm robotics in mines, and they proved to be good in exploration and cooperative working in complex ground. The uses of Unmanned Aerial Vehicles (UAVs) concerning mine surveying, inspection, and hazard assessment have become popular, and according to Shrivastava [8] [9], aerial monitoring with UAVs is claimed to produce significant productivity and safer work environments. Additional autonomous earthmoving systems reviewed by Nguyen and Ha held developments in perception, control, and human and robot teaming in changing environments, as highlighted by Nguyen and Ha [11].

Intelligent perception-based advanced safety systems have demonstrated positive outcomes. Imam et al. [15] [14] performed an extensive overview of the computer vision-based anti-collision systems and reached the conclusion that intelligent sensing and real-time warning systems play a major role in minimizing the number of accidents caused by collisions in underground mines. Ge et al. [12] addressed the topic of standardization of intelligent mining transportation systems and stated the necessity of interoperability and safety-compliant autonomous vehicle frameworks.

Simulation and training technologies also contribute to efficient deployment. Špirková et al. [20] demonstrated that Virtual Reality (VR)-based simulation combined with robotic implementation improves operational planning and workforce preparedness. The more general trends in the field of intelligent robotics were also systematically analyzed by Licardo et al. [19], which supports the significance of Artificial Intelligence (AI)-based autonomy, perception, and human-machine interface in industries, including mining.

Overall, the literature indicates that robotics and automation are linked to high safety and efficiency benefits during mining operations. However, the literature is likely to talk about specific technologies or usage one by one. The research gap in the study lies in the integrated frameworks that might be applied to evaluate safety performance, operational efficiency, and system interoperability in real time, which dictated the requirement of having a holistic assessment model in the intelligent mining systems.

MATERIALS AND METHODS

Research Design and Approach

The research design is a systematic mixed-methods research design that will be used in this study to determine the effects of robotics and automation on the safety performance and operational efficiency in mining activities. The approach combines a literature-based structured evaluation plan with an analytical framework using technologies to analyze autonomous systems, robotic platforms, and intelligent monitoring systems used in surface and underground mines. Qualitative insights are included as well as quantitative performance indicators to ensure that the entire evaluation of the automation-based safety improvement and productivity increase is made.

Data Sources and Technology Selection

Peer-reviewed journals, industrial reports, and documented mining case studies addressing the robotic and automated mining applications were used as a source of secondary data. The technological solutions examined are autonomous haulage systems, autonomous drilling and inspection units, unmanned aerial vehicles, autonomous patrol robots, swarm robotics, and intelligent sensor networks. Technologies have been chosen according to their applicability to operations, maturity of use, autonomy degrees, and reported safety and efficiency results, with a focus on systems used in the actual mining activities or pilot projects.

Safety Performance Assessment

The reduction in the number of accidents, exposure of the worker to the hazardous areas, the effectiveness of the hazard detection systems, and the reliability of the real-time surveillance systems were indicators of the safety performance. The traditional mining process was compared to the automated mining process to determine the degree to which the robotic system-controlled risks that were caused by geotechnical instability, exposure to toxic gases, collisions of the equipment used, and human errors.

Operational Efficiency Evaluation

The operational efficiency was measured based on such metrics as the rate of equipment utilization, the reduction in the cycle time, the output of productivity, the energy efficiency, and unplanned downtime. The autonomous and semi-autonomous systems were examined based on the capability to enhance the consistency of task execution, accuracy in scheduling, and the use of resources. Normalization of performance metrics that were reported across studies was done, where needed, to allow meaningful cross-technology and cross-environment comparisons.

Integrated Analytical Framework

A combined analysis framework was established to help correlate the safety performance indicators with the operational efficiency indicators at once. This framework allows combining the overall impact of robotics and automation, which involves the interplay between the automation level, sensing, control architecture, and environmental complexity to examine system-level performance trade-offs and synergies.

The scheme of the overall analytical framework workflow is introduced in Figure 1. This figure describes the flow of data sources and technology selection to two parallel streams of evaluation addressing the performance of safety and operation efficiency. These streams of assessment are then incorporated into one stream of analysis that looks at the integrated effect of robotics and automation. The framework is summarized by comparative validation in various mining conditions, the general results of which are improvement in safety enhancement and operational efficiency.

Validation and Comparative Analysis

The suggested framework was confirmed by evaluating it against the background of surface mining, underground hard rock mining, and coal mining. The trends in the performance were analyzed to determine the consistent advantages and disadvantages of automation in different conditions of operation. The level of sensitivity analysis was done to determine the effect of the autonomy level and the complexity of the environmental factors on the outcomes of safety and efficiency.

Ethical and Practical Considerations

The methodological evaluation included ethical and practical considerations such as the workforce transition, safety of the human-robot interaction, system reliability, and the risk of cybersecurity. Robotics and automation were evaluated as safety-enhancing technologies that could be used in addition to human control, but not in full substitution of human capabilities to make responsible and sustainable use of intelligent mining systems.

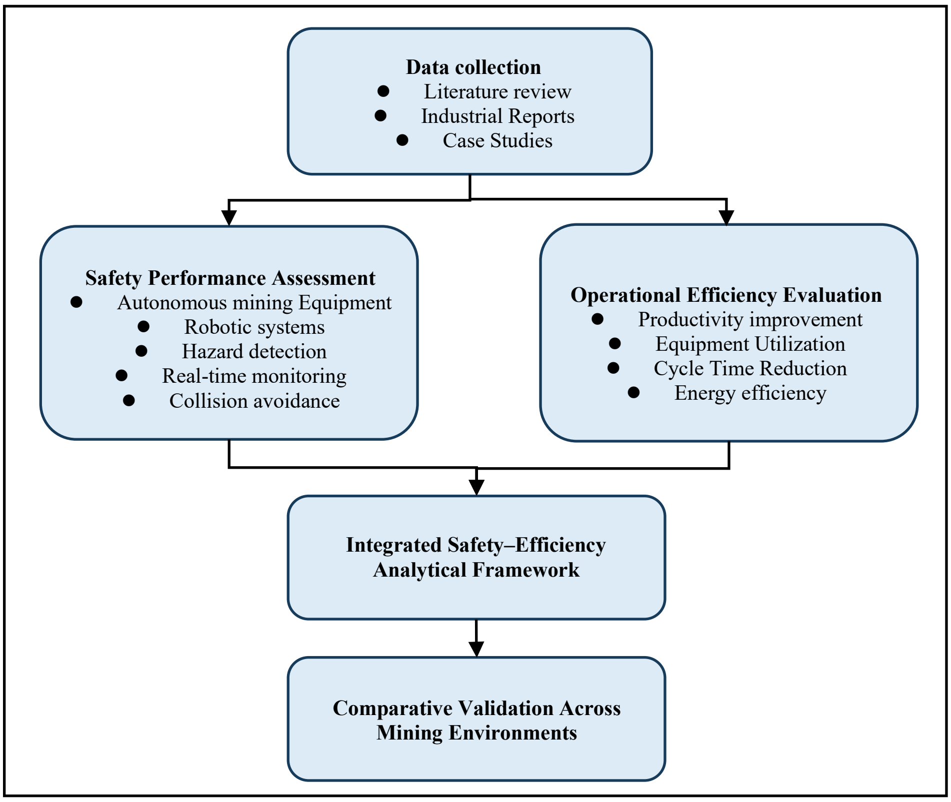

Figure 1. Integrated methodological framework for evaluating robotics and automation in mining

RESULTS

Safety Performance Outcomes

The use of robotics and automation technologies showed that there is a significant enhancement of mining safety performance at the surface and underground levels. Comparative analysis of the traditional and automated mining system operations showed that there was a steadily decreasing number of accidents and the number of workers exposed to dangerous areas. Autonomous patrol robotization, the UAV-based surveillance systems, and intelligent sensor networks substantially improved the real-time hazard detection, especially in gas-prone and geotechnically unreliable zones. The relative safety gains in underground mining settings were improved, given that fewer people were found in restricted and dangerous areas.

The Accident Reduction Rate (ARR) was used to quantify safety improvement and is expressed as:

$$ARR(\%) = \frac{A_c - A_a}{A_c} \times 100 \qquad (1)$$

In equation (1), A_c represents the number of accidents in conventional mining operations, and A_a represents the number of accidents after automation deployment.

Table 1 summarizes the observed safety performance indicators across different mining environments.

Table 1. Safety performance comparison between conventional and automated mining operations

Mining environment	Accident frequency (conventional)	Accident frequency (automated)	Reduction (%)	Worker exposure reduction (%)
Surface mining	18.4 ± 2.1	11.2 ± 1.6	39.1	42.6
Underground mining	27.8 ± 3.4	13.5 ± 2.2	51.4	58.9
Coal mining	24.6 ± 2.9	12.8 ± 1.9	48.0	55.3

Table 1 captures the effects of robotics and automation on the safety performance in the surface and underground and coal mining settings. The findings indicate that there is a clear decrease in the number of accidents following the introduction of automated systems as opposed to the traditional operations. The underground mining exhibits the largest number of accidents and worker exposure reduction, which demonstrates how automation can be applied to environments that are very risky and restricted. Overall, the findings indicate that the overall effect of robotic and automated technologies on the safety of workers is large, as they minimize the exposure of human beings to hazardous conditions in different mining settings.

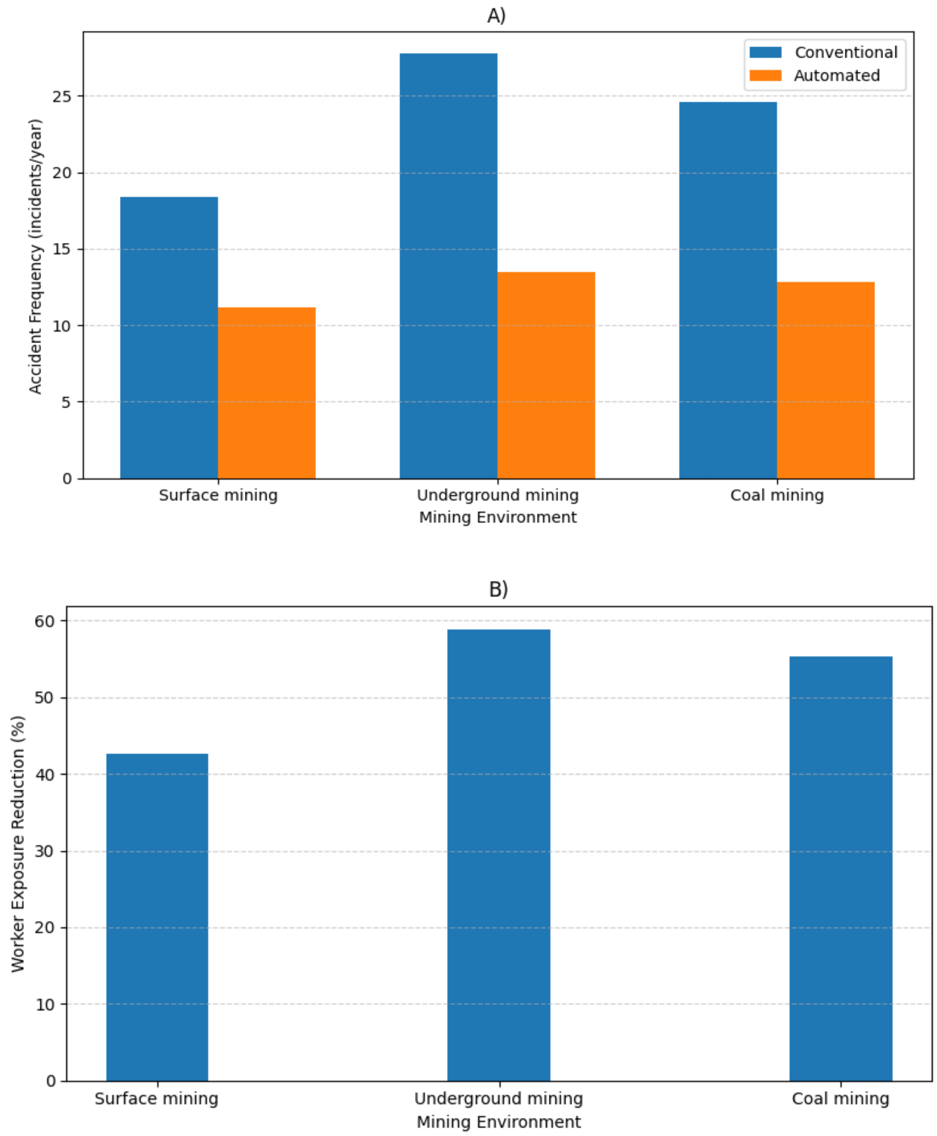

Figure 2. Safety performance improvement through robotics and automation in mining environments

Figure 2 panel (A) displays the comparison of the frequency of accidents during conventional and automated mining operations in surface, underground, and coal mining conditions, according to which the number of accidents has significantly decreased after the implementation of automation. In Panel (B), the percentage reduction in worker exposure to hazardous mining zones shows that robotics and automation are very beneficial to the safety of workers, especially in underground and coal mining work.

Operational Efficiency Enhancement

The measures of operational efficiency have also shown significant growth after the implementation of autonomous and robotic systems. The automated hauling, drilling, and inspection platforms reduced the number of cycles and increased the percentage of equipment utilization, as well as reducing the unplanned downtime. Uncontrolled systems were more predictable in their systems and less dynamic in the variation of their performance compared to the manual operations.

Equipment Utilization Rate (EUR) was calculated using the following expression:

$$EUR(\%) = \frac{T_o}{T_t} \times 100 \qquad (2)$$

In equation (2), T_o is the operational time of the equipment, and T_t is the total available time.

Productivity Improvement Index (PII) was used to evaluate output efficiency and is defined as:

$$PII(\%) = \frac{P_a - P_c}{P_c} \times 100 \qquad (3)$$

In equation (3), P_c and P_a represent productivity before and after automation, respectively.

Table 2. Operational efficiency metrics before and after automation

Metric	**Conventional operation**	**Automated operation**	**Improvement (%)**
Equipment utilization (%)	62.5 ± 4.3	81.7 ± 3.8	30.7
Average cycle time (min)	18.2 ± 1.9	12.6 ± 1.4	30.8
Productivity output (t/day)	4,150 ± 320	5,460 ± 410	31.6
Unplanned downtime (%)	14.8 ± 2.6	8.1 ± 1.7	45.3

Table 2 presents key operational performance indicators before and after the implementation of robotics and automation. The automated operations recorded a significant improvement in the number of equipment utilization and daily productivity, as well as a considerable decrease in average cycle time and unplanned downtime. The offered improvements prove the effectiveness of automation in order to make operations and resource usage more reliable and enhance mining as a whole.

Integrated Safety–Efficiency Assessment

The composite analytical framework indicated that there is a strong positive relationship between performance in safety and operational efficiency. Systems of greater autonomy and sophisticated sensing abilities exhibited the concomitant decrease in the rate of accidents and increase in productivity. The Safety–Efficiency Index (SEI) was developed to capture this relationship and is defined as equation (4):

$$SEI = \frac{ARR \times PII}{100} \qquad (4)$$

Higher SEI values indicate balanced gains in safety and efficiency.

Table 3 summarizes the combined impact of robotics and automation on accident reduction and productivity improvement across different mining scenarios. Safety -Efficiency Index (SEI) in underground mining is the largest, and this means that the balance between the highest gains in safety and operating efficiency is that of underground mining, followed by coal mining and surface mining. These results prove the appropriateness of automated systems in risky and complicated mining firms.

Table 3. Integrated safety–efficiency performance across mining scenarios

Mining scenario	Accident reduction (%)	Productivity improvement (%)	SEI
Surface mining	39.1	28.4	11.1
Underground mining	51.4	34.2	17.6
Coal mining	48.0	32.1	15.4

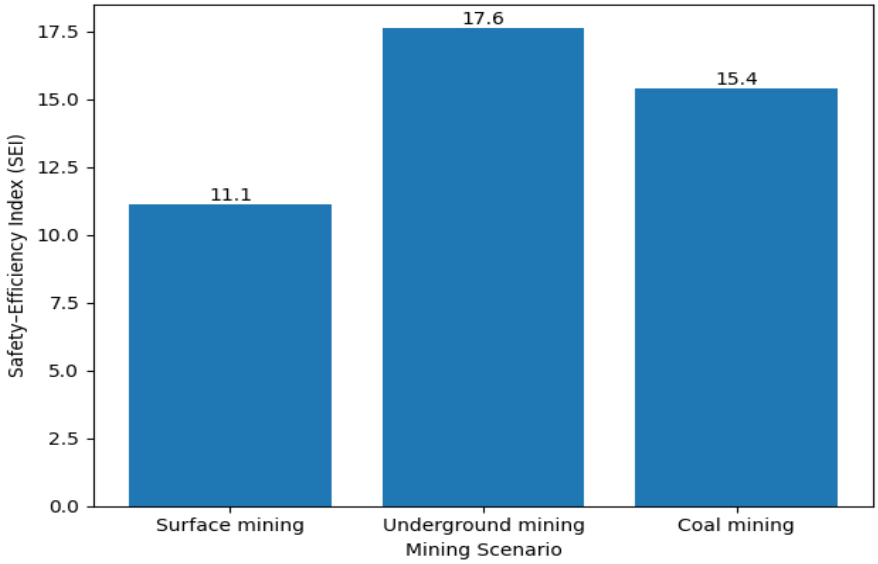

Figure 3. Safety–efficiency index comparison across mining scenarios

Figure 3 depicts the values of the Safety Efficiency Index (SEI) of surface mining, underground mining, and coal mining. The comparison indicates the synergies between robotics and automation in terms of the decrease in the rate of accidents and the subsequent increase in productivity at the same time. Increased values of SEI would be a sign of greater incorporation of safety and operational efficiency enhancement; whereby underground mining would show the highest overall advantage of automated and robotic systems.

Technology-Specific Performance Trends

The analysis by technology revealed that autonomous haulage systems and robotic drilling units were the most beneficial to productivity increase, whereas autonomous patrol robots, UAVs, and sensor-based collision avoidance systems proved to be the most important in enhancing safety. Swarm robotics and AI-based surveillance systems demonstrated good prospects of adaptive and scalable functionality, but their performance relied on the complexity of the environment and the reliability of communication.

Validation Across Mining Environments

The proposed framework was tested and confirmed in a variety of mining conditions. The pattern of performance was the same in the surface, underground, and coal mining, and there were slight differences due to the geological conditions and infrastructure preparedness. The sensitivity analysis has shown that the level of automation and sensor integration has a stable positive effect on the safety and efficiency indicators, which proved the main hypothesis of this work.

DISCUSSION

The findings of the present research make it evident that the introduction of robotics and automation technologies can bring significant improvements in the safety performance and the efficiency of the operations in a variety of mining settings. The frequency of accidents that are reduced after the implementation of automation proves the efficiency of autonomous systems in reducing human contact with dangerous conditions. The rates of accident reduction, 39.1% in surface mining, 51.4% in underground mining, 48.0% in coal mining, point to human-machine interaction risk being minimized through continuous monitoring and remote operation, which makes the results of safety benefits more significant in high-risk settings and confined environments. In line with this, the exposure of workers to dangerous areas is reduced by a factor of up to 58.9% in underground mining, which strengthens the importance of robotics in improving situational awareness and real-time hazard detection. The benefits of automation in the mining business are also supported by the results of operational efficiency. The use of the equipment grew to 81.7% as compared to 62.5%, which is 30.7% higher, and the average cycle time also decreased to 30.8%. There was an increase in productivity output by 31.6% and a reduction in unplanned downtime by 45.3%, suggesting that the autonomous systems can enhance productivity as well as operational reliability and consistency. These benefits are explained by efficient scheduling, minimized human error, and predictive capabilities of intelligent control and sensing systems. The integrated SEI offers a detailed analysis of the overall effect of automation on the mining performance. Underground mining attains the highest SEI value of 17.6, followed by coal mining with 15.4 and surface mining with 11.1, which shows that automation is the most beneficial in the environment where the inherent safety risks and the complexity of operations are higher. The improved efficiency of productivity associated with the reduction of accidents positively correlates with the idea that the traditional trade-off between safety and efficiency is not applicable, but smart automation allows for improving both factors simultaneously. Specific to technology trends, it also shows that the main productivity gains are associated with autonomous haulage and robotic drilling systems, UAVs, patrol robots, and collision avoidance systems are the most important in terms of safety improvement. In general, the results confirm the developed integrated framework and allow considering the hypothesis that robotics and automation play a major role in improving safer, more efficient, and sustainable mining processes.

CONCLUSION

This paper has shown that a combination of robotics and automation technology is very helpful in increasing the performance in terms of safety and efficiency of operations in surface, underground, and coal mining conditions. According to the quantitative results, significant decreases in the number of accidents were observed, including the rate of accident reduction of 39.1% in surface mining, and 51.4% Underground mining, and 48.0% in coal mining. Worker exposure reduction in underground mining was minimized by 58.9%, highlighting the usefulness of automated and remote-controlled systems in high-risk and confined workplaces. Improvement of operational efficiency was also equal. The automatic equipment usage rose by 30.7%, productivity output was enhanced by 31.6%, average cycle time was cut by 30.8%, and the unplanned downtime was decreased by 45.3% after the deployment of automation. These results attest that robotics and automation not only increase safety but also reduce the use of resources and improve mining productivity. The integrated SEI also confirmed the combined benefits of the automation, as underground mining had the largest SEI value (17.6), coal mining had the next highest value (15.4), and surface mining had the lowest value (11.1). This shows that smart automation allows achieving concomitant safety and efficiency improvements, as opposed to a trade-off between them. Future studies ought to be on field validation on a large scale, adaptive human-robot collaboration, and the incorporation of artificial intelligence to forecast safety and repair. Also, intelligent mining systems will require the sustainable implementation of challenges such as the interoperability of systems, upskilling of the workforce, and cybersecurity to enhance the adoption of intelligent mining systems.

REFERENCES

[1] Obosu M, Frimpong S. Advances in automation and robotics: The state of the emerging future mining industry. Journal of Safety and Sustainability. 2025 May 29. https://doi.org/10.1016/j.jsasus.2025.05.003

[2] Long M, Schafrik S, Kolapo P, Agioutantis Z, Sottile J. Equipment and operations automation in mining: a review. Machines. 2024 Oct 9;12(10):713. https://doi.org/10.3390/machines12100713

[3] Du H, Chan L, Tong J, Raad R, Naghdy F, Guo Q, Yu Y, Islam MR, Tubbal F, Ros M, Li Z. Industrial progress of robotic automation in mining applications: A survey. Mining, Metallurgy & Exploration. 2025 Mar 4:1-20. https://doi.org/10.1007/s42461-025-01219-y

[4] Waghmare GH, Thelkar AR, Babu SB, Katre R, Kumar A, Mahender K. Robotics in Underground Mining for Improved Worker Safety and Efficiency. International Journal of Environmental Sciences. 2025 Jun 2:279-86. https://doi.org/10.64252/kaq8mv14

[5] Onifade M, Said KO, Shivute AP. Safe mining operations through technological advancement. Process Safety and Environmental Protection. 2023 Jul 1; 175:251-8. https://doi.org/10.1016/j.psep.2023.05.052

[6] Flores-Castañeda RO, Olaya-Cotera S, López-Porras M, Tarmeño-Juscamaita E, Iparraguirre-Villanueva O. Technological advances and trends in the mining industry: a systematic review. Mineral Economics. 2025 Jun;38(2):221-36. https://doi.org/10.1007/s13563-024-00455-w

[7] Tan J, Melkoumian N, Harvey D, Akmeliawati R. Evaluating swarm robotics for mining environments: Insights into model performance and application. Applied Sciences. 2024 Oct 2;14(19):8876. https://doi.org/10.3390/app14198876

[8] Kim H, Choi Y. Development of autonomous driving patrol robot for improving underground mine safety. Applied Sciences. 2023 Mar 14;13(6):3717. https://doi.org/10.3390/app13063717

[9] Shrivastava A. Unmanned aerial vehicles (UAV) in mining sector: Enhancing productivity and safety. Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering. 2025 Dec;239(15):2219-35. https://doi.org/10.1177/09544100251352429

[10] Pouresmaieli M, Ataei M, Taran A. Future mining based on internet of things (IoT) and sustainability challenges. International Journal of Sustainable Development & World Ecology. 2023 Feb 17;30(2):211-28. https://doi.org/10.1080/13504509.2022.2137261

[11] Nguyen HA, Ha QP. Robotic autonomous systems for earthmoving equipment operating in volatile conditions and teaming capacity: a survey. Robotica. 2023 Feb;41(2):486-510. https://doi.org/10.1017/S0263574722000339

[12] Ge S, Wang FY, Yang J, Ding Z, Wang X, Li Y, Teng S, Liu Z, Ai Y, Chen L. Making standards for smart mining operations: Intelligent vehicles for autonomous mining transportation. IEEE Transactions on Intelligent Vehicles. 2022 Oct 11;7(3):413-6. https://doi.org/10.1109/TIV.2022.3197820

[13] Topolsky D, Topolskaya I, Plaksina I, Shaburov P, Yumagulov N, Fedorov D, Zvereva E. Development of a mobile robot for mine exploration. Processes. 2022 Apr 27;10(5):865. https://doi.org/10.3390/pr10050865

[14] Wu X, Li H, Wang B, Zhu M. Review on improvements to the safety level of coal mines by applying intelligent coal mining. Sustainability. 2022 Dec 7;14(24):16400. https://doi.org/10.3390/su142416400

[15] Imam M, Baïna K, Tabii Y, Ressami EM, Adlaoui Y, Benzakour I, Abdelwahed EH. The future of mine safety: a comprehensive review of anti-collision systems based on computer vision in underground mines. Sensors. 2023 Apr 26;23(9):4294. https://doi.org/10.3390/s23094294

[16] Cacciuttolo C, Guzmán V, Catriñir P, Atencio E, Komarizadehasl S, Lozano-Galant JA. Low-cost sensors technologies for monitoring sustainability and safety issues in mining activities: advances, gaps, and future directions in the digitalization for smart mining. Sensors. 2023 Aug 1;23(15):6846. https://doi.org/10.3390/s23156846

[17] Kamran-Pishhesari A, Moniri-Morad A, Sattarvand J. Applications of 3d reconstruction in virtual reality-based teleoperation: A review in the mining industry. Technologies. 2024 Mar 15;12(3):40. https://doi.org/10.3390/technologies12030040

[18] Onifade M, Adebisi JA, Shivute AP, Genc B. Challenges and applications of digital technology in the mineral industry. Resources Policy. 2023 Aug 1; 85:103978. https://doi.org/10.1016/j.resourpol.2023.103978

[19] Licardo JT, Domjan M, Orehovački T. Intelligent robotics—A systematic review of emerging technologies and trends. Electronics. 2024 Jan 29;13(3):542. https://doi.org/10.3390/electronics13030542

[20] Špirková S, Straka M, Saniuk A. VR Simulation and Implementation of Robotics: A Tool for Streamlining and Optimization. Applied Sciences. 2024 May 23;14(11):4434. https://doi.org/10.3390/app14114434