ISSN 1840-4855
e-ISSN 2233-0046

Original Scientific Article
http://dx.doi.org/10.70102/afts.2025.1833.1013

INTEGRATING SUSTAINABLE PRACTICES AND AUTOMATION IN MINING ENGINEERING EDUCATION FOR THE MODERN ERA

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Received: September 14, 2025; Revised: October 18, 2025; Accepted: December 01, 2025; Published: December 20, 2025

SUMMARY

Sustainable practice and automation in the field of mining engineering are becoming a fundamental component of educating the future engineers to respond to the challenges facing a changing mining industry. As mining operators are increasingly being pressured to utilize more environmentally sustainable practices and to adopt new automation technologies, the type of education provided to these future engineers has never been more important. This study will explore the integration of sustainable practice and automation technology in the current mining engineering education curriculum. Additionally, this study will assess the current state of mining engineering education through the use of a mixed-method approach (including a survey sent to both academic institutions and industry experts) and identify existing gaps that need to be addressed. Although sustainable development practices have already been incorporated into some mining engineering education programs, only about 40% of those surveyed currently offer specialized courses that deal with automation technology. In addition, 65% of surveyed industry experts believe that automation has the potential to greatly enhance the environmental sustainability of the mining industry. Finally, the study will discuss how mining engineering programs can incorporate sustainability and automation into the curriculum by developing interdisciplinary programs, partnering with industry, and providing students with hands-on training using the latest technologies available. Incorporating all of these components allows educational institutions the ability to provide graduates with the tools needed for leading operations that are at the forefront of sustainable and sophisticated technology within the field of mining. To this end, this paper has recommended further enhancements to the curriculum, improvements to instructional delivery, and increased opportunities to partner with industry to prepare students for the challenges that the future of mining engineering typically presents.

Key words: *sustainable practices, automation, mining engineering education, curriculum integration, environmental sustainability, technological advancements, industry collaboration.*

INTRODUCTION

The mining industry plays an essential role in the global resource extraction system, supporting the economies of many countries. In recent years, however, there has been increasing scrutiny placed on the environmental effects of mining, particularly habitat destruction and pollution of waterways from mine runoff, as well as greenhouse gas emissions associated with energy use for mining operations [4][5], and because of the increasing worldwide demand for minerals and other materials, sustainable mining practices will need to be developed to limit the impact of mining on the environment [6]. In addition, the rapid development and advancement in automation technologies will continue to create opportunities to improve mine operational efficiencies and reduce both capital and labor costs while also helping to mitigate environmental risks. Unfortunately, the education of many current mining engineers has not kept pace with the rapid advancements in technology and, instead, has relied on traditional teaching approaches and failed to integrate cutting-edge automated technologies and sustainable practices into the curriculum [7]. The failure to incorporate the innovations that will continue to shape the future of the industry into mining engineering education has limited future mining engineers' ability to meet the diverse challenges of the mining industry [8].

To maintain their competitiveness in today's ever-changing world, mining engineering schools must recognize and adapt to the growing global demand for automation and sustainability. As such, mining engineering schools need to adequately prepare their students for future mining operations that will be characterized by increased complexity, automation, and environmental responsibilities. Therefore, it will be essential for mining engineering schools to include automation, sustainability, and digitalisation as part of their curriculum. By ensuring that their graduates are equipped with the necessary skills and knowledge to lead the future of automated and sustainable mining operations, mining engineering schools can better fulfil their cumulative obligation to prepare students for careers within the mining sector.

Research Questions

1. How effectively are automation technologies integrated into current mining engineering curricula, and what impact does this integration have on students' readiness to meet industry demands?

2. What are the key barriers and opportunities for incorporating sustainable practices into mining engineering education, as perceived by faculty, students, and industry experts?

3. How does the level of industry collaboration in mining engineering education programs influence the development of students' practical skills in automation and sustainability?

Key Contributions

- Examines the discrepancy between the industry's demand for automated and sustainable processes and the mining engineering programs now offered.

- Evaluates how automation technology and sustainable practices are incorporated into current educational frameworks.
- Identifies the main obstacles standing in the way of fully integrating sustainability and automation into mining education.
- To improve educational outcomes, it suggests curricular changes and methods for industry-academia cooperation.
- Provides institutions with useful advice on how to match mining engineering curricula with industry technical developments and global sustainability objectives.

The remainder of the paper is structured as follows: in Section 2, relevant literature and current trends in the mining industry are summarised; in Section 3, the research methodology for gathering and analysing data using a mixed-methods approach is described; Section 4 provides a discussion of key findings and presents an overview of the data collected and analysed; in Section 5, specific recommendations regarding future curriculum design and future research opportunities to facilitate industry collaboration and technology adoption, are outlined.

LITERATURE REVIEW

Past studies confirm that mining and geotechnical engineering fields will be implementing changes toward digitizing processes, implementing sustainable practices, and reforming their educational fields [10]. This study in particular emphasises the need for engineers in today's mining industry to adopt a sustainable approach that utilises innovation in technology and aligns with the principles of environmental management [1]. This document discusses how the mining industry can use the latest technologies in monitoring, automation, and data-based decision making to reduce negative impacts on the environment, improve resource efficiency, and improve the efficiency of operations [9][17]. Sustainability is more than just a defined requirement; it is an approach that will support the long-term economic sustainability and social acceptance of mine developments.

The report looks at this technological view as well as how the roles of mining engineers are transforming, suggesting that the education of mining engineers should include sustainability [2][11]. The report demonstrates the manner in which global course/ag curriculum is changing to correspond with the European Green Deal, as well as with the sustainable development goals, by combining traditional aspects of technical skills with interdisciplinary knowledge, environmental awareness, and ethical practices [12]. The authors emphasize that future mining engineers will require these skill sets to deal with the complex challenges in society, the economy, and the environment [13]. The paper also discusses the effects of the Fourth Industrial Revolution on geotechnical engineering; the introduction of automation, big data, IoT, and Artificial Intelligence has changed the way the mining industry operates [3][14]. These technologies can be applied immediately to support mining operations, especially in the areas of subsurface evaluations and ground stability; they improve real-time monitoring, risk management, and predictive capabilities. Presently, technology has a wide variety of uses in the mining industry, especially for evaluating subsurface conditions and ground stability, while also providing enhanced capabilities in real-time monitoring, risk management, and predictive modelling. As identified by the authors, the potential barriers to effectively utilising these technologies are both limited experience and adequate resources as well as high capital investment costs to utilise these technologies.

Through review of the documentation for these studies, it is clear that the future of mining engineering will be focused on (1) advancing the use of digital technologies; (2) developing a sustainable practice; and (3) utilising updated training and education methods. Furthermore, the literature establishes that when considering the future of mining due to the 4IR and sustainability initiative, mining professionals will need to create a plan to implement these technologies and practices; to develop an understanding of how these technologies work together, the mining industry must create a framework for professional training of mining personnel to fully implement the use of the 4IR and sustainability initiative [15] [16].

PROPOSED METHODOLOGY

To integrate automation and sustainable practices in mining engineering education, the recommended strategy consists of multiple phases with defined objectives to assess the current state of educational programs in mining engineering, identify gaps, and provide recommendations for systematic improvement of the curriculum. Each phase of development utilizes a combination of qualitative and quantitative data collection methodologies in order to be able to fully evaluate both the potential for incorporating sustainability and automation themes into the overall curriculum as well as the potential challenges to do so [17].

Study Design

The collection of primary data on the current status of mining engineering education will be accomplished through surveys sent to post-secondary institutions offering mining engineering degree programs. The surveys will focus on the level of integration of automation technology (e.g., robots, autonomous vehicles, AI) into educational programs, and the level of sustainable practices in educational programs (e.g., resource efficiency, reducing environmental impact, reclamation). Industry experts will be interviewed to assess the significance of these two elements from both an academic and professional perspective. Faculty, students, and industry representatives will also provide input on the relevance and impact of including sustainability and automation themes in the mining engineering curriculum.

Data Collection and Analysis

Quantitative and qualitative statistical methods will be employed to collect and assess data that have been collected through survey, interview, or institutional report methods by using statistical software, such as SPSS or Jamovi for quantitatively analyzed data, and NVivo for qualitative analysis.

The analysis will center on three general areas: (1) Curriculum content, to calculate what percentage of educational institutions include classes related to automation and related sustainable practices; (2) Industry collaboration, to assess the extent of collaboration between education providers and business leaders to incorporate physical automation technologies into curricula; and (3) Student readiness, to evaluate how well current mining engineering students are prepared to meet industry expectations of automation and sustainable practices in their fields.

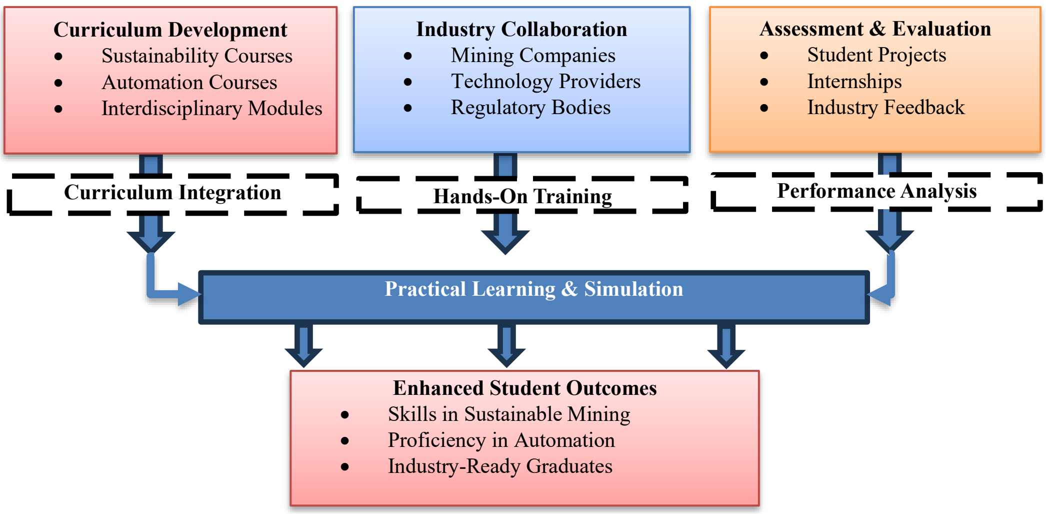

Figure 1. Proposed system architecture for integrating sustainability and automation in mining engineering education

To analyse the relationship between perceived industry requirements and curriculum content, various statistical models of regression and ANOVA will be used in this analysis. Thematic analysis of qualitative data will reveal key themes associated with challenges and opportunities associated with the integration of automation and sustainability into mining engineering education.

The proposed architecture (Figure 1) for integrating automation and sustainability into mining engineering education highlights both information flow among varying components (e.g., student assessment indicators, industry involvement, curriculum development) and how these parts work together to improve student learning experiences with hands-on learning as well as simulated environments; thus, leading to increased abilities regarding both automation-related and sustainable mining skills.

Mathematical Description

Mathematical models are utilized to analyze how changes in the overall curricular structure affect how automation and sustainability will be integrated into mining education. E will be considered the educational product of mining engineering (see Equation 1), and Equation 1 indicates how the production of E relates to different variables,

$$E = f(C, I, T) \quad (1)$$

where C stands for the curriculum's content, which includes the quantity of courses on automation and sustainability. The number of industry relationships and the degree to which real-world technologies are included into the curriculum serve as indicators of the degree of industry involvement. T stands for the technologies utilized in the classroom, including automation tools, simulation software, and practical training apparatus.

The objective is to optimize C, I, and T in order to maximize E. To find the best balance between these variables, a multi-objective optimization method might be applied. Equation 2 illustrates how the ideal weights for each factor can be found using a model such as the Weighted Sum Method (WSM),

$$E_{opt} = w_1 C + w_2 I + w_3 T \quad (2)$$

Where w_1, w_2, and $w_3$are the weights assigned to each factor based on their importance, and $E_{opt}$is the optimal educational output. These weights can be determined based on feedback from industry experts, faculty, and students.

Curriculum Reformation and Recommendations

Educators involved in mining engineering will receive specific recommendations based on the results of this process. To better represent the increasing impact of automation technologies in today's mining operations, the recommendations will focus on creating new courses or specialty modules that will introduce courses in robotics, artificial intelligence, and autonomous vehicle operation. Also, new topics related to the sustainable use of natural resources such as resource-efficient mining, environmental reclamation, and concepts of a "circular economy" will be added to existing courses associated with sustainability. To help prepare graduates with the knowledge and skills necessary to meet current and future demands in the mining industry, the recommendations will recommend stronger collaborations between academic institutions and those in the mining industry for purposes of integrating practical innovations, case studies, and industry-oriented research into their teaching and learning methods.

In addition to the proposals to enhance real-world learning experiences related to automation and sustainable technologies, the recommendation will place emphasis on experiential learning, such as internships and field-based projects. Through the synergy of experiential learning and classroom education, graduates will be better prepared to support the industry's movement towards greater sustainability and technological sophistication.

RESULTS AND DISCUSSIONS

Software Details

A suite of software was utilized to analyse data and implement the system. Jamovi was selected for statistical analysis; ANOVA testing, correlation analysis and descriptive statistics were completed using this software package. For regression analyses and hypothesis tests that are more complicated, SPSS is used. NVivo assists with qualitative analysis (thematic analysis or classifications) of survey and interview responses.

Dataset Details

The data being analysed is comprised of a dataset of mining engineering students that received automation and sustainable practices education through programmes. The dataset consists of data from 400 mining engineering students across eight universities in the 2024-2025 academic year. The dataset contains demographic information about the student population such as age, gender and educational background along with academic information about them (grades, project performance, test scores). In addition to demographic and diagnostic academic performance information, it also contained responses to surveys evaluating the incorporation of automation technology and sustainable practices into curricula, as well as qualitative feedback from industry professionals regarding how well prepared students will be to address real mining challenges. The dataset also includes information gathered from students in hands-on training of automation and sustainable practices through simulation or other methods.

Performance Comparison

The following indicators were used to assess the pupils' performance:

Sustainability Knowledge: Students' comprehension of sustainable mining methods is evaluated using these criteria. Equation 3 illustrates how it is assessed using a combination of written tests and practical activities.

$$\text{Sustainability Score} = \left(\frac{\text{Correct Responses}}{\text{Total Questions}}\right) \times 100 \quad (3)$$

Automation Proficiency: Equation 4 assesses students' application of automation ideas by having them complete simulation-based tests and automation projects.

$$\text{Automation Score} = \left(\frac{\text{Correct Tasks Completed}}{\text{Total Tasks}}\right) \times 100 \quad (4)$$

Industry-Readiness: Equation 5 assesses students' readiness for issues in the real world of business. It is predicated on input from business partners on how well students performed during internships and real-world projects.

$$\text{Industry-Readiness Score} = \left(\frac{\text{Positive Evaluations}}{\text{Total Evaluations}}\right) \times 100 \quad (5)$$

Project Completion Time: Equation 6 shows how long it takes students to do practical projects using automation and sustainability.

$$\text{Project Completion Time} = \frac{\text{Time Taken by Student}}{\text{Average Time}} \quad (6)$$

Student Satisfaction: Students' opinions of the curriculum's efficacy provide the basis of Equation 7. Students' satisfaction with the incorporation of automation and sustainability into their curriculum is measured using a Likert-scale survey.

$$\text{Satisfaction Score} = \left(\frac{\text{Total Satisfaction Points}}{\text{Max Points}}\right) \times 100 \quad (7)$$

Performance Evaluation

Experiments with various curricular integration models that utilized varying degrees of integration with automated technology, industrial involvement, and sustainable practices provided the data used to evaluate student performance

Table 1. Performance comparison of different curriculum integration models

Metric	Baseline Curriculum	50% Integration with Industry	75% Integration with Industry	Fully Integrated with Industry and Automation
Sustainability Score (%)	65.5	78.3	85.2	92.5
Automation Proficiency Score (%)	70.2	80.1	88.0	95.0
Industry-Readiness Score (%)	60.4	73.5	80.0	90.0
Project Completion Time (hrs)	50	45	35	30
Student Satisfaction (%)	75	85	90	95

The comparison of student performance in four distinct curricular integration models is presented in Table 1. Each curricular integration model differed with respect to the level of integration of automation technologies, industry engagement, and sustainable practices. Performance measurements (KPIs) included Sustainability, Automation Proficiency, Industry Readiness, Project Completion Time and Student Satisfaction. Each KPI provides evidence that increased integration of automated technologies and industry partners enhances student performance by improving Sustainability, Automation Proficiency, Industry Readiness, reducing Project Completion Time, and increasing Student Satisfaction.

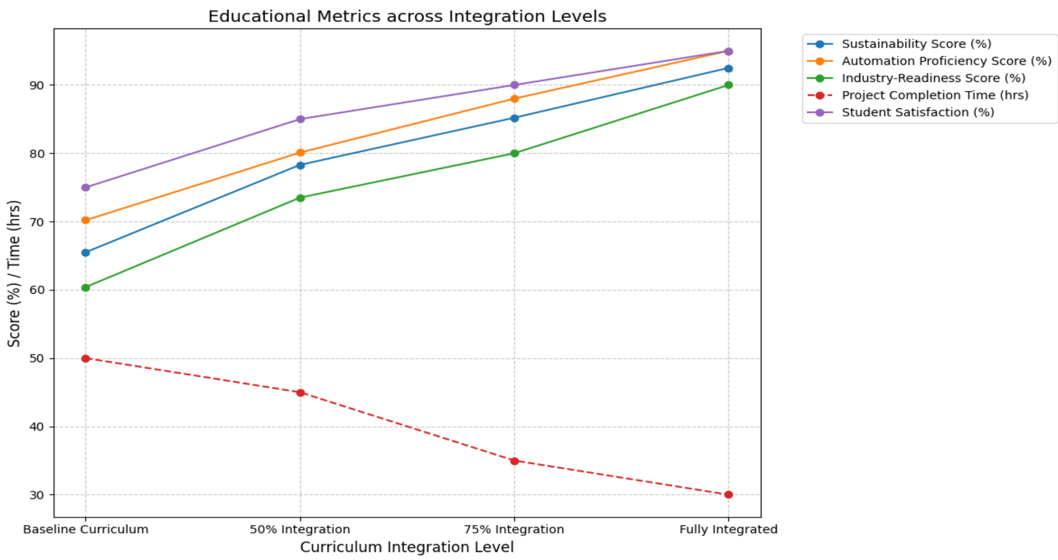

Figure 2. Educational metrics across integration levels

Graphically, the relationship between curricular integration models and student performance is shown in Figure 2. The measures displayed on the Y-axis include Sustainability Score (%), Automation Proficiency Score (%), Industry Readiness Score (%), and Student Satisfaction (%). All measures indicate significant improvement as the degree of curricular integration increases; this is especially true for Automation Proficiency, Industry Readiness, and Sustainability Scores. Conversely, the Y-axis indicates decreasing Project Completion Time (hours) as the degree of integration increases, indicating improved efficiency.

DISCUSSION

The purpose of this research is to highlight the need for integrating new technologies and sustainable mining practices into the education of the next generation of mining professionals in order to be better prepared to cope with the future challenges in the industry. There exists a noted gap between what is necessary for modern mining operations versus how mining engineering programs are currently prepared to provide students with the knowledge and skills to perform in an increasingly automated workplace. Though many programs have begun to introduce sustainable mining practices such as improved resource efficiency and reduced environmental impacts, few have developed specific courses around automation technology. The gap in education surrounding automated systems has important consequences for future productivity and safety in the mining industry. As demonstrated in the results of this research, industry experts believe automation technology can significantly reduce mining's negative impact on the environment by reducing process variance, minimizing waste, and improving the use of resources; thus, students currently are not being afforded the opportunity to gain hands-on experience with automated systems, thereby exacerbating the inconsistency between automation and education.

Recommendations

The study suggests curricular changes that integrate automation and sustainability technology, as well as improved industry-academia cooperation, to address these issues. Mining engineering schools can better prepare students to meet the expectations of the business by offering multidisciplinary courses that integrate automation technology with environmental science and practical training opportunities in the future. In the end, this integration will contribute to the development of a future engineers who can oversee automated, sustainable mining operations. To guarantee that its graduates are equipped for the quickly developing profession of mining engineering, educational institutions must give priority to these changes.

CONCLUSION

The findings from this research illustrate that there exists a significant gap between current mining engineering education and the growing demands of the mining industry regarding sustainability and automation. Specific findings indicate that while sustainability has become part of many curriculums, only 40% of the institutions surveyed offered any coursework related to automation. Furthermore, 65% of industry professionals believe that automation has the potential to have a significant positive effect on the environment in the mining industry. By providing a comparison between multiple methods of curriculum integration, this report shows that more effective student achievement can be achieved through closer integration of both industry collaboration and automation. Furthermore, based on statistical analysis, students who graduated from schools that had implemented both automation and sustainability into their respective curriculums achieved scores of 92.5% on sustainability and 95% on automation versus those who graduated from schools that had not included automation and sustainability into their curriculums. Therefore, in order to properly prepare students for the current mining challenges, the educational structures must align with the industrial expectations. Future research may focus on the long-term effects of these curricular changes on the mining workforce by looking at the performance of graduates in actual operations that incorporate both automation and sustainability. The efficiency of various teaching strategies, such experiential learning, in improving students' comprehension of automation technology could also be the subject of future research. Furthermore, studies on how industrial collaborations help academic programs incorporate real-world automation systems would offer insightful information about how to improve academia-industry cooperation.

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