Afghan International Journal of Science (AIJS)

Publisher: Afghan International Islamic University

Website: https://aijs.aiiu.edu.af

e-ISSN: 3134-5859

Prioritizing Modern Mining Technologies for Afghanistan Using a Multi-Criteria Decision Analysis Framework

Zaman Nihzat[1*], Aref Naimzad[2], Mohammad Fahim Weyaar[3]

[1&3]Afghan International Islamic University (AIIU), Department of Mining Engineering & Management, Faculty of Engineering, Kabul, Afghanistan

[2]Afghan International Islamic University (AIIU), Department of Industrial Engineering, Faculty of Engineering, Kabul, Afghanistan

Abstract

The mining sector in Afghanistan, with its vast mineral resources, faces challenges in adopting modern technologies due to infrastructure and economic limitations. Despite the availability of various modern mining technologies, no prioritization framework has been proposed for Afghanistan. This research fills this gap by presenting an evidence-based prioritization in Afghanistan. Fifteen modern mining technologies were identified through a systematic literature review, and weights for five important criteria were determined through a survey of 100 Afghan mining experts. The Simple Additive Weighting (SAW) method was used for prioritization, and sensitivity analysis was conducted to confirm the validity. The findings indicate that GIS & RS, UAVs, Air & Dust Pollution Monitoring, and Renewable Energy Technologies are the four top priorities. Conversely, technologies such as AI, Blockchain, Automation, and Digital Twins are ranked lowest. This framework provides a strategic tool for gradual, context-appropriate adoption of Afghanistan's mining sector by policymakers and investors.

Keywords: Afghanistan, Mining, Technologies, Multi-Criteria Decision Analysis (MCDA), Technologies Prioritization

Article History

Published: June 30, 2026

Accepted: May 17, 2026

Revised: May 17, 2026

Received: February 18, 2026

Cite as: Nihzat, Z., Naimzad, A., & Weyaar, M. F. (2026). Prioritizing Modern Mining Technologies for Afghanistan Using a Multi-Criteria Decision Analysis Framework. *Afghan International Journal of Science 2*(2), 163-181. DOI: https://doi.org/10.66546/aijs.v2i2.52

Introduction

The global mining industry is transitioning into the digital age. Technologies like Artificial Intelligence (AI), the Internet of Things (IoT), Remote Sensing (RS), and Automated Systems are fundamentally changing the way mines are explored, mined, and managed. These technologies promise increased productivity, safety, and environmental sustainability (Battulwar et al., 2020; Zhang & Li, 2020). For developed countries, this transformation is a strategic opportunity. However, for a country like Afghanistan with rich mineral reserves but

[*]Email: zamannihzat@gmail.com (Corresponding Author)

Link to the Article: https://aijs.aiiu.edu.af/index.php/aijs/article/view/52

limited infrastructure, scarce capital, and an inexperienced technical workforce, the critical question is: Which of these modern technologies should be prioritized for implementation to yield the greatest returns in the shortest time and with the lowest possible risk?

Afghanistan possesses valuable mineral reserves that can drive economic development. However, the exploitation of these resources has always been accompanied by major challenges, including reliance on traditional methods, low productivity, environmental degradation, and ineffective monitoring (Nero & Rahmani, 2022; Nero, 2025). Adopting new technologies can be a solution to overcome this impasse. However, the wrong choice of technology (such as investing in fully automated systems in the absence of stable electricity) not only fails but also wastes the country's limited financial resources and undermines trust in the technology.

Previous studies have examined the benefits of different technologies in mines in developed countries (e.g., Tang, 2024 on Artificial Intelligence; Yaghini et al., 2022 on Robotics; Forkuor et al., 2020 on Geographic Information System (GIS)). Also, Multi-Criteria Decision-Making (MCDM) methods have been widely used for technology selection in various industries (Kumar & Pamucar, 2025; Torbacki, 2025). However, there is a major research gap: no systematic, evidence-based study has prioritized modern mining technologies for a country like Afghanistan, given its specific conditions and severe constraints. Most studies either examine technologies in isolation or have selection criteria tailored to developed-country contexts. This gap has confused Afghan policymakers and investors in decision-making and led to ineffective planning.

The main objective of this study is to fill this gap by providing an evidence-based, mixed-methods (qualitative-quantitative) prioritization framework tailored to the Afghan context. The present study answers this key question: Given the infrastructural, financial, and skills constraints in Afghanistan, what is the logical and practical order for implementing modern mining technologies, and on what criteria is this prioritization determined?

Furthermore, this article evaluates the technologies most commonly used in the mining sector and their direct and indirect impacts on mineral exploration, mine development, mineral extraction, and the reclamation of mining areas. It also examines the technologies currently employed in Afghanistan's mining sector, their current utilization levels, and their potential applicability to future mining operations.

The innovation of this study lies in its integrated methodology. On the one hand, a systematic review has been conducted (based on the PRISMA guidelines) to extract objective, quantitative evidence on the performance of the top 15 technologies. On the other hand, by surveying 100 key stakeholders in the Afghanistan mining sector (including engineers, managers, lecturers, specialists, and inspectors), five critical technology selection criteria were identified and assigned weights. Then, by combining these two sets of data and using the Simple Additive Weighting (SAW) method (a type of MCDM). Final evidence-based rankings are presented. The SAW method was chosen because of its transparency, simplicity, and compatibility with the survey data. The framework is not only scientific but also weighted by those with a deep understanding of the field realities in Afghanistan. The overall structure of this article is shown in Conceptual Diagram 1.

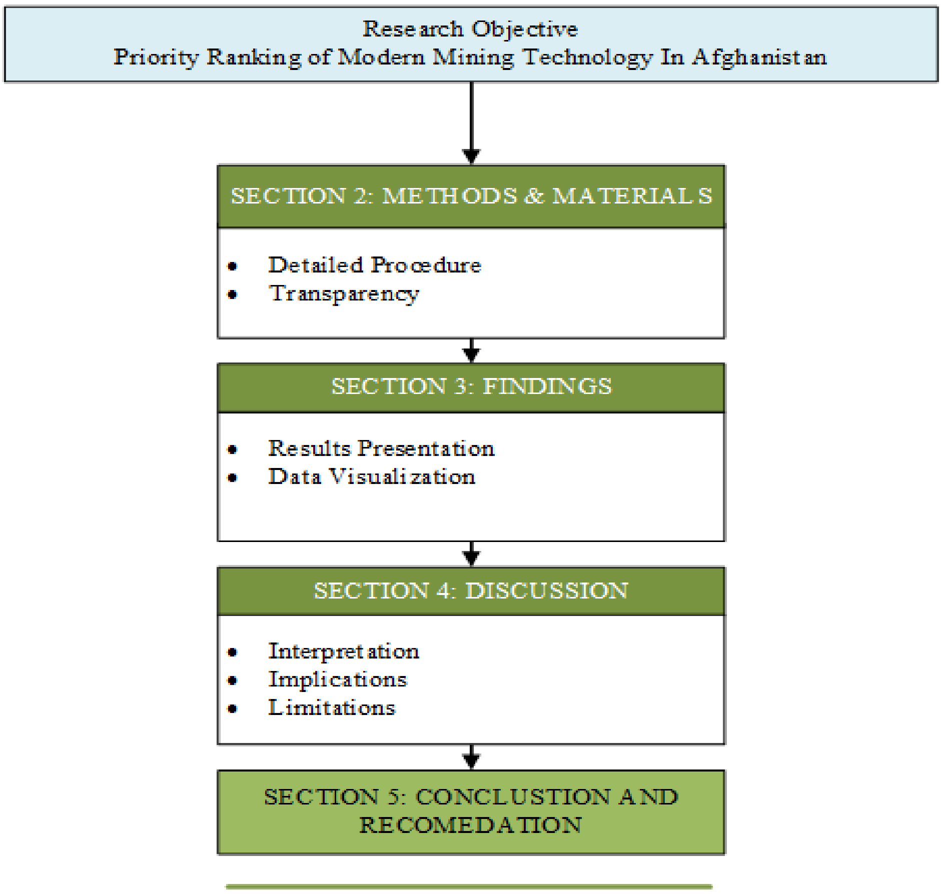

Figure 1: Structure of the article

Methods and Materials

This study used a sequential mixed exploratory design (qualitative-quantitative) within a pragmatic paradigm to prioritize modern mining technologies for implementation in Afghanistan. The methodology consisted of four stages.

Study Design and Overview

This study was conducted with the purpose of and is descriptive-analytical in nature. The sequential design included a preliminary qualitative stage (systematic literature review) to identify and score technologies and criteria, followed by a quantitative stage (stakeholder survey) to weight the criteria and localize the findings to Afghanistan. Finally, the results of both stages were merged using an MCDM method to determine the final ranking of priorities. This approach was chosen to ensure that the findings were evidence-based and also relevant to the context.

Step 1: Technology Identification and Data Extraction (Systematic Review). A systematic literature review was conducted following the PRISMA guidelines to identify common modern mining technologies and their characteristics.

Searches were conducted in Google Scholar, ScienceDirect, Springer, and IEEE Explore databases for publications between 2015 and 2025. Common keywords for this research included: ("modern technology in the mining industry" also "digital technologies in the mining"), ("sustainable mining technology"), ("artificial intelligence in the mining"), ("Internet of Things for mining monitoring"). Initial searches yielded hundreds of records. After screening titles and abstracts, 252 full-text articles were assessed for eligibility based on relevance, data availability, and focus on publication date (prioritizing 2020–2025). According to a structured checklist, qualitative and quantitative data were extracted for each technology, such as key data on applications, quantified benefits (e.g., percent increase in production, cost reduction), cost indicators (quality: high/medium/low), infrastructure requirements, challenges, and documented experiences in developing countries.

The full text of the systematic review and detailed data extraction are beyond the scope of this article. This article presents only the data that formed the evidence base for the objective, and only 53 of the mentioned papers are used for scoring technologies in Step 3. The 15 Technologies identified through this process, with scoring, are listed at the end of this section (Methods) in Table 2.

Step 2: Criteria Selection and Weighting (Stakeholder Survey). A survey was conducted among key mining stakeholders in Afghanistan to extract and weight the criteria for technology selection.

Sampling and Population

The target population included university Lecturers in mining engineering departments, engineers and managers of the private and public mining sector, and experts and inspectors of the Ministry of Mines and Petroleum of Afghanistan. A non-probability sampling strategy (purposive and snowball) was used to reach 100 participants, as follows: 60 from private/public mines, 20 from the Ministry of Mines and Petroleum, and 20 from university lecturers. The geographical distribution of the target respondent groups across key mining regions/ provinces is shown in Figure 2.

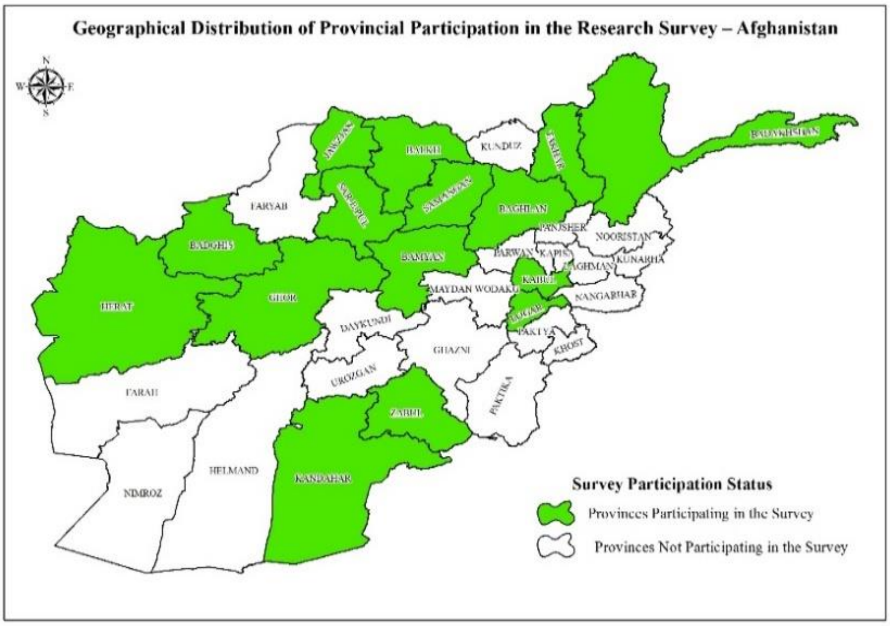

Figure 2: Map of Afghanistan, Highlighting Key Mining Provinces where the Stakeholder Survey was Distributed

Data Collection

A structured questionnaire was developed based on Phase 1 findings in the Afghan context. The questionnaire included demographic questions and a main section on five selection criteria. C1, C2, C3, C4, C5 (Every technologies which have the lower cost according to economical value and having most benefits for entire process of mining works, the employee should learn easily and comfortably work with the machinery in specific periods of time it means that should need less time for learning the technologies, After installation need short periods of time for collaboration of the machine and being economic beneficial, and the machinery should easy be repaired in Afghanistan and by technical expert of Afghanistan Engineer, according to rule and regulation of Afghanistan should be useable in country it means that not be constrained according to usage)

- **C1:** Low initial cost.
- **C2:** Ease of training and maintenance.
- **C3:** Rapid financial return.
- **C4:** Compatibility with Afghanistan's existing infrastructure.
- **C5:** Government technical or financial support.

The questionnaire was distributed electronically over a period of 4 weeks.

Validity and reliability: Content validity was confirmed through review by three mining and academic experts. A test showed high internal reliability for the scale items (Cronbach's alpha = 0.85).

Ethical Considerations

Informed consent was obtained from all participants. Anonymizing responses maintained confidentiality, and participants were informed of their right to withdraw.

Step 3: Technology Performance Scoring. The 15 technologies identified in Step 1 were scored using the five weighted criteria from Step 2. Scoring was not based on opinion, but on objective evidence extracted from the systematic review. A transparent scoring key was used (e.g., a "very high cost" documented in the literature = score 1 for C1; "moderate cost" = score 3; documented "rapid return on investment" = score 5 for C3). This process produced a 15x5 decision matrix. See Table 2 below.

An example of the scoring process for one technology (Renewable Energy Technology) is provided in Table 1 to illustrate the methodology.

Table 1: *Detailed Scoring Example for one Technology (Clean & Renewable Energy Technology)*

Criteria	Score (1-5)	Justification (Based on Systematic Review)	Source(s)
C1: Low Initial Cost	2	High initial capital cost for infrastructure and storage.	(Mahir et al., 2024)

C2: Easy Training/Maintenance	3	Requires significant technical expertise for design and operations.	(Mahir et al., 2024)
C3: Rapid Income/Savings	5	Cost Savings 25-30% on average, >70% in isolated sites for Hybrid PV-Diesel Plants.	(Ellabban & Alassi, 2021)
C4: Compatibility with AFG Infra.	4	In mineral-rich regions like the Katanga province, solar resources often have an LCOE below US$0.06/kWh.	(Deshmukh et al., 2018)
C: Gov. Support Potential	4	A critical success factor is implementing policies that provide fiscal incentives, such as tax breaks and grants.	(Seraj & Olaide, 2024)

Due to the large size of the table, the full scoring and reference sources for each technology are provided at the end of this section (Methods) in Table 2.

Step 4: Prioritization Using the SAW Method. The SAW method was applied to calculate the final priority scores.

Normalization: The decision matrix was normalized to produce the R matrix. For the criteria (all five in this case), the calculation followed Eq. (1) (Sembiring et al., 2019).

$$r_{ij} = x_{ij}/max\ (x_j) \tag{1}$$

Weighted score calculation: The final priority score (V_i) for each technology (i) was calculated as Eq. (2), using the weights (W_j) from the survey (Sembiring et al., 2019, p. 3).

$$V_i = \sum_{j=1}^{5}(W_j \times r_{ij}) \tag{2}$$

Ranking: The technologies were ranked in descending order based on their (V_i) score.

Sensitivity Analysis

To test the robustness of the priority-ranking SAW, a sensitivity analysis was conducted. The weight of each of the five criteria was systematically varied by ±20%, while the other weights were kept proportionally constant. The resulting changes in the final ranking order were observed and recorded. Finally, it was determined which rankings were stable and which were sensitive to weight fluctuations.

Data Analysis Tools

Descriptive statistics from the survey were analyzed using Excel and SPSS. MCDM calculations and the SAW method were performed in Excel. OriginPro is used to draw the Graphs.

Input Data Summary (Continuation of Step 3). This matrix is a continuation of Step 3. All technologies identified in the systematic review and qualitative assessment of the literature were scored on five critical criteria for the Afghanistan context. Due to the large size of the matrix, only the sources on which the scores were calculated are listed in Table 2, without the main text. The detailed scoring matrix and the text are provided in the Supplementary Materials.

Table 2: *Complete Scoring Matrix with references for all identified Modern Mining Technologies*

No	Technology	Score for every criterion (1-5)					Key Justifying Source (from Systematic Review)
		C1	C2	C3	C4	C5	
1	AI	1	2	5	2	2	(Tang, 2024; Dotsenko et al., 2021; Zhironkina & Zhironkin, 2023; Zhang & Li, 2020)
2	IoT	3	3	4	3	3	(Kim et al., 2020; Bartoli & Hernández-Ramírez, 2023; Zvarivadza et al., 2024)
3	Automation & Robotics	1	2	5	1	2	(Pincheira et al., 2022; Gromov, 2020; Leung et al., 2023; Yaghini et al., 2022; Zhou et al., 2017)
4	GIS & RS	4	3	4	4	3	(Forkuor et al., 2020; Plessis et al., 2022; Yang & Müterthies, 2020; Moomen et al., 2022; Buttulwar et al., 2020)
5	Drones (UAVs)	4	3	5	4	3	(Daou et al., 2022; Buttulwar et al., 2020)
6	Blockchain	2	2	3	2	2	(Onifade et al., 2024; Mugurusi & Ahishakiye, 2022; Shvachych et al., 2022)
7	Digital Twins	1	1	4	1	1	(Cranford, 2023; Shi et al., 2020; Caciutolo et al., 2025)
8	Renewable Energy	2	3	5	4	4	(Mahir et al., 2024; Ellabban & Alassi, 2021; Deshmukh et al., 2018; Seraj & Olaide, 2024)
9	Water Recycling Tech.	2	2	4	3	3	(Hamraoui et al., 2024; Feo et al., 2020; Grewar, 2019; Zhu et al., 2024)
10	Air & Dust Pollution Monitoring	4	3	4	4	4	(Lee, 202; Brown Requist et al., 2024; Tripathi et al., 2024; Ziętek et al., 2020; Saleem & Ayalew, 2025)
11	Mining Planning & Simulation Software	2	2	4	3	2	(Loginov et al., 2020; Cacciuttolo et al., 2025; Moradi Afrapoli et al., 2024; Torres et al., 2020)
12	Data Management Systems	3	2	4	3	3	(Hazrathosseini & Moradi, 2023; Aziz et al., 2020; Xia et al., 2018; Wang et al., 2023; Vangu et al., 2023)
13	HSE Management Systems	2	2	4	2	1	(Zhou et al., 2018; Amalina & Larasati, 2020; Guntur Suryaning et al., 2023)
14	Tailings Recycling Tech.	2	2	3	3	3	(Cacciuttolo & Atencio, 2023; Maest, 2023; Araujo et al., 2022)
15	VR/AR Training Tech.	2	3	4	2	2	(Kamran-Pish et al., 2024; Strzałkowski et al., 2025)

Findings

Demographics

The stakeholder survey on the weighting of the criteria was conducted by a diverse, experienced group of 100 experts from the Afghan mining sector. Profiles of the respondents' ages, education, and the types of mines in which they worked, along with the minerals they extracted, are summarized in Table 3.

Table 3: *Demographics of survey respondents (n=100)*

Age Group	Frequency	Percentage (%)
<25	2	2%
25-35	66	66%
36-45	28	28%
>45	4	4%
Education level	Frequency	Percentage (%)
Diploma	4	4%
Bachelor's Degree	46	46%
Master's Degree	48	48%
PhDs	2	2%
Types of Mines	Frequency	Percentage (%)
Surface Mines	26	26%
Underground Mines	30	30%
Bothe	18	18%
None	26	26%
Mineral Type Expertise	Frequency	Percentage (%)
Coal	40	37%
Limestone & Marable	22	21%
Stones	16	15%
Gold	12	11%
Polymetallic (Lead & Zinc)	10	9%
Chromite	8	7%

As shown in Table 3, the sample consisted of a highly educated and experienced professional base. The majority (66%) were 25 to 35 years old, and 94% had at least a bachelor's degree. Depending on the type of mines, a higher percentage of respondents worked in underground mining, especially in coal mines.

The distribution of respondents by their main job title is shown in Figure 3. Mining engineers comprised the largest group (43.8%). Following the engineers were university lecturers (20.8%) and Ministry of Mines employees (20.8%). This combination ensured that the weights collected reflected an excellent mix of practical field experience, academic insight, and supervisory perspective.

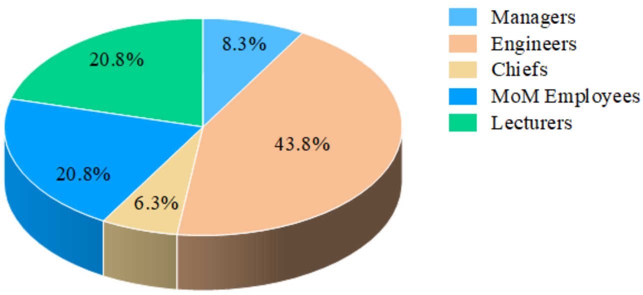

Figure 3: Chart showing the percentage distribution of respondents by job position

Weighting of Evaluation Criteria

The relative importance assigned by stakeholders to the five selection criteria is presented in Table 4. The second criterion, "ease of training and maintenance" (C2), and the fifth criterion, "government technical or financial support" (C5) received the highest weights. This indicates that ease of adoption and external support are the main concerns for implementing the technology in the Afghan context. The weights of all criteria were close to each other, indicating a balanced consideration of cost, compatibility, and benefit factors. The relative importance of these criteria is also shown visually in Figure 4 below.

Table 4: *Stakeholder-derived weights for selection criteria*

Criterion	Description	Mean Importance (1-5)	Normalized Weight (Wj)
C1	Low initial cost	3.86	0.199
C2	Easy training and maintenance	3.96	0.205
C3	Rapid increase in income or savings	3.72	0.192
C4	Compatibility with Afghanistan's existing infrastructure	3.90	0.201
C5	Government technical or financial support potential	3.92	0.203
Total		19.36	1.000

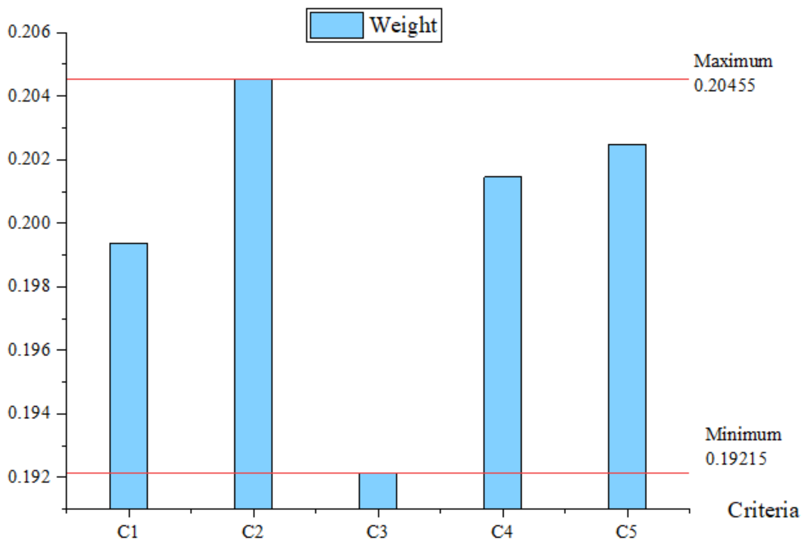

Figure 4: A graphical representation of the weighted importance (Wj) of the five selection criteria as determined by expert judgment.

Technology Priority Ranking

Applying the SAW method to the performance scores (derived from Table 2) and the criterion weights (Table 4) yielded the final priority ranking for the 15 technologies, as shown in Table 5.

Table 5: *Final Priority Ranking of Modern Mining Technologies for Afghanistan*

Rank	Technology	Final Score (Vi)
1	GIS & RS	0.9616
2	Drones (UAVs)	0.9190
3	Air & Dust Pollution Monitoring Technologies	0.8806
4	Clean & Renewable Energy Technologies	0.8598
5	Data Management Systems	0.7527
6	IoT	0.7300
7	Water Recycling Technologies	0.7028
8	VR & AR Training Technologies	0.6802
9	Mining Planning & Simulation Software	0.6623
10	Tailings Recycling Technologies	0.6239
11	Health, Safety & Environment (HSE) Management Systems	0.6213
12	AI	0.5621
13	Blockchain	0.5331
14	Automation & Robotics	0.5097
15	Digital Twins	0.4130

The final rankings are visually summarized in Figure 5, which provides a clear comparative view of the weighted scores across all technologies.

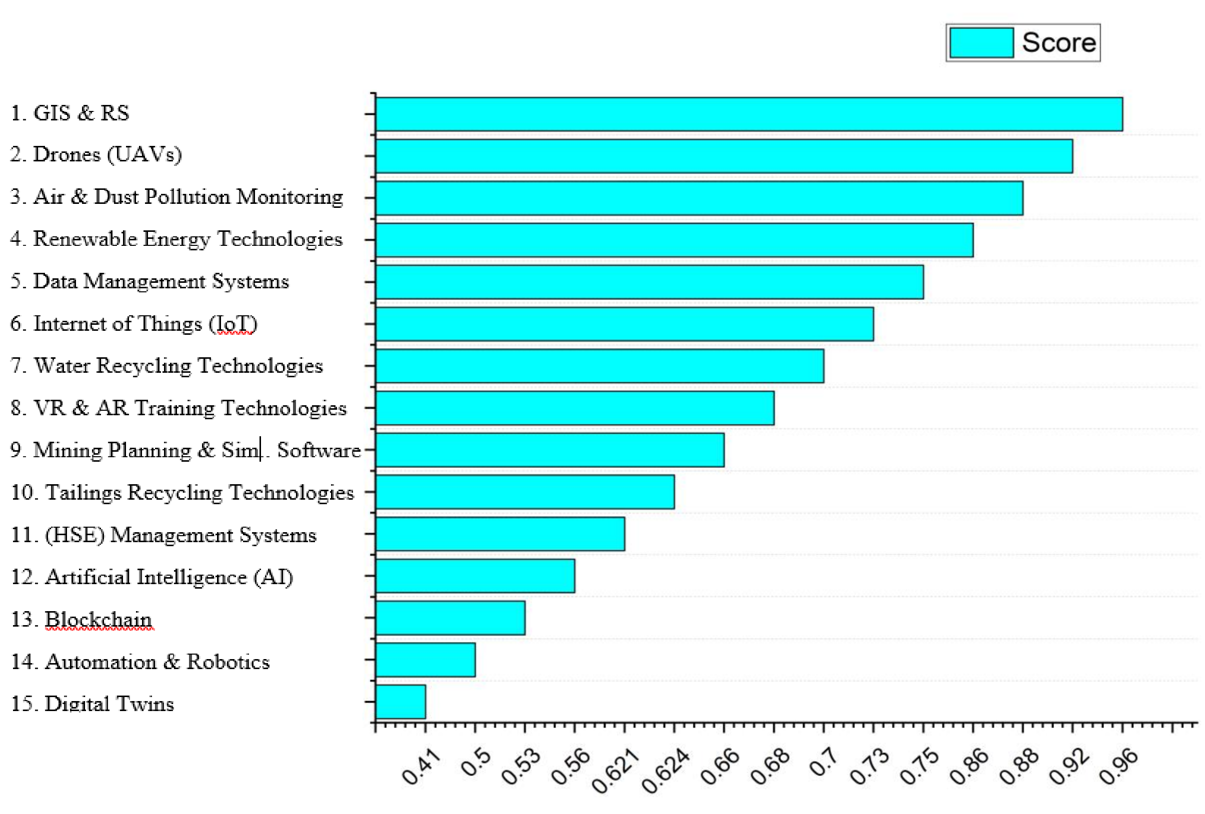

Figure 5: Final ranking of priorities for modern mining technologies in Afghanistan using the SAW method

This analysis reveals three clear and evidence-based conclusions for the Afghanistan mining sector: First, a set of basic and accessible technologies, such as GIS & RS, Drones, Air & dust Monitoring, and Renewable Energy, emerges as the top and undisputed priorities. Second, a group of high-potential but infrastructure-dependent technologies, Data Management Systems, IoT, Water Recycling, VR & AR Training, Mining Planning & Simulation Software, Tailings Recycling, and HSE Management Systems, falls in the middle, warranting phased implementation. Third, the most complex and capital-intensive systems, like artificial intelligence, digital twins, and full automation, are not currently aligned with Afghanistan's immediate constraints and rank lowest.

Sensitivity Analysis

Table 6: *Sensitivity analysis results (±20% difference in individual criteria weights)*

Technology	R0	R1	R2	R3	R4	R5	Robustness
GIS & RS	1	1	1	2	1	1	Highly Stable (Top Tier)
Drones UAVs	2	2	2	1	2	3	Highly Stable (Top Tier)
Air & Dust Pollution Monitoring Tech.	3	3	3	4	3	4	Highly Stable (Top Tier)
Renewable Energy Tech.	4	4	4	3	4	2	Highly Stable (Top Tier)
Data Management Systems	5	5	7	5	5	5	Stable
IoT	6	6	5	6	8	7	Moderately Sensitive
Water Recycling Technologies	7	8	8	7	6	6	Moderately Sensitive
VR & AR Training Tech.	8	9	6	8	10	8	Sensitive
Mining Planning & Simulation Software	9	10	9	9	7	9	Moderately Sensitive
Tailings Recycling Tech.	10	11	10	13	9	10	Sensitive
HSE Management Systems	11	7	11	10	11	12	Sensitive
AI	12	13	12	12	12	11	Stable (Bottom Tier)
Blockchain	13	12	13	14	13	13	Stable (Bottom Tier)
Automation & Robotics	14	14	14	11	14	14	Stable (Bottom Tier)
Digital Twins	15	15	15	15	15	15	Highly Stable (Bottom Tier)

In this table: R0= Base Rank, R1= Rank when (C1+20%), R2= Rank when (C2+20%), R3= Rank when (C3+20%), R4= Rank when (C4+20%), R5= Rank when (C5+20%)

As calculated in Table 6, the sensitivity analysis confirms the robustness of the main findings. The top four technologies (GIS, Drones, Pollution Monitoring, and Renewable Energy) and the last-ranked technology (Digital Twins) are very stable. They maintain their positions even with significant fluctuations (±20%) in the criterion weight. This underlines the strength of their prioritization for Afghanistan. The ranking of Data Management systems (ranked 5) also shows considerable stability. However, the technologies ranked 6th to 11th (notably IoT and Water Recycling) show moderate to high sensitivity. This means that their exact order can change if stakeholders' priorities (weights) for criteria such as ease of training (C2) or infrastructure compatibility (C4) change. This suggests that while the top and bottom priorities are clear and actionable, the middle of the list comprises suitable technologies whose final selection can be guided by specific policy emphases or local circumstances.

Discussion

This study provides a practical, evidence-based framework for prioritizing modern mining technologies in Afghanistan. The main findings, which combine a global systematic review and local stakeholder input, represent not just a simple list, but a context-based strategic agenda.

Interpreting the Rankings: Context-based adaptation as a Determinant

The stable prioritization of GIS and Remote Sensing RS, Drones, Air and Dust Pollution Monitoring technologies, and Renewable Energy directly reflects the immediate needs and infrastructure constraints of Afghanistan. These technologies scored highest on the two most heavily weighted criteria: low initial cost (C1) and compatibility with Afghanistan's existing infrastructure (C4). The systematic review shows that, despite their significant benefits, these technologies have lower initial requirements. For example, GIS uses satellite data, which is often free, and requires only a computer and a basic internet connection (Forkuor et al., 2020). This makes it a low-cost, low-complexity, high-impact solution for resource-constrained areas. Drones are similarly a low-cost alternative to the costly methods of traditional aerial mapping (Battulwar et al., 2020). The consistency of these technologies' rankings in the sensitivity analysis also suggests that they are the least risky and safest starting points for investment.

Technologies that ranked low, such as Artificial Intelligence, Blockchain, Automation, and Digital Twins, are due to their direct conflict with current realities in Afghanistan. The literature clearly identifies high capital intensity and strong dependence on advanced digital infrastructure as the main challenges of these technologies in developing countries (Cacciuttolo et al., 2025; Zhang & Li, 2020; Zhou et al., 2017). Therefore, their low ranking is not a judgment on their global potential, but a realistic assessment of their incompatibility with the current Afghanistan context.

Robustness of Results: From Sensitivity Analysis

The sensitivity analysis, which systematically varied each criterion's weight by ±20%, confirmed the robustness of the overall prioritization. The positions of the top four technologies (GIS, UAVs, Air and dust Pollution Monitoring, and Renewable Energy) and the last-ranked technology (digital twins) remained unchanged across all scenarios. This consistency strongly suggests that prioritizing these technologies for Afghanistan is a reliable, low-risk decision. These technologies do not involve minor changes in stakeholder preferences. However, the analysis showed that the order of the middle-ranking technologies (ranks 6–11), especially IoT, Virtual Reality, and Training technologies, could change if changes were made to criteria such as "ease of training (C2)" or "infrastructure compatibility (C4)." This insight is important: while the list of top technologies to invest in is clear, the exact order of implementation in the middle group can be flexible, depending on local conditions or specific policy emphases.

Practical Implications: A Step-by-Step Roadmap

The results of this study can be translated into a practical roadmap for Afghan stakeholders. proposing a three-step strategy in Table 7.

- For policymakers: The focus should be on facilitating Phase 1 through pilot projects, education, and smart regulation. Complex technologies ranked low are a warning against premature, disproportionate investments.
- For industry and investors: Phase 1 and 2 technologies are the least risky and have a faster payback in the current context. Investment in environmental monitoring can help gain social acceptance.
- For universities: The high weight of the "Easy to train and maintain (C2)" criterion indicates the need to revise curricula to train specialists in Phase 1 areas (e.g., GIS, UAV piloting).

Table 7: *Proposed step-by-step strategy for technology adoption in Afghanistan mines*

Phase	Title	Target Technologies (by Rank)	Key Actions	Time Goal
1	Foundation and Capacity Building	1-4 (GIS & Rs, Drones/UAVs, Air & Dust Monitoring, Renewable Energy)	▪ Government-led pilot projects ▪ Training of local specialized personnel ▪ Development of monitoring standards	Short-term (1-2 years)
2	Integration and Optimization	5-10 (Data Management, IoT, Water Recycling)	▪ Integration of information systems ▪ Financial incentives for clean technologies ▪ Public-Private Partnerships	Medium-term (3-5 years)
3	Transformation and Advancement	11-15 (AI, Automation, Digital Twins)	▪ Upgrading national digital infrastructure ▪ Context-aligned applied research and development ▪ Targeted foreign investment attraction	Long-term (+5 years)

Limitations of the Study

This study has limitations that point the way for future research. First, the scoring, although based on objective evidence, also involved some expert judgment in quantifying the qualitative findings. Second, detailed cost-benefit analyses for each technology at the level of specific projects in Afghanistan could clarify financial priorities. Third, the current study is static; dynamic modeling could show how priorities will change as infrastructure and skills improve over time. Finally, validating this framework through case studies in one or two Afghan mines would be a valuable final step in translating this theory into practice.

Conclusion

This study developed a systematic, evidence-based approach to selecting and prioritizing modern mining technologies in Afghanistan, drawing on a global systematic review and expert opinions via the SAW technique. The results of the study have shown that simple, low-cost technologies with low infrastructure requirements, i.e., GIS and RS, UAVs, Air and Dust Pollution Monitoring, and Renewable Energy Technologies, have the highest priority. In contrast, technologies such as Artificial Intelligence, Blockchain, Automation, and Digital

Twins have the lowest priority, indicating that their implementation in Afghanistan would be premature without prerequisite infrastructure development and capacity building. A sensitivity analysis of the results, varying the criteria weights by +/- 20%, shows that the ranking of the technologies remains the same.

This study makes a significant contribution to the field by showing that the prioritization of technologies in a resource-scarce developing country cannot simply follow global trends. The scientific justification for the study is evident in the scoring system and expert criteria, which reflect the country's reality. The practical application of the study is also substantial because it enables policymakers to allocate scarce resources effectively, investors to invest in profitable opportunities, and development agencies to fund projects transparently. This can prevent guesswork-based decisions, thereby accelerating development with minimal investment risk.

This research adds value to the body of knowledge through a replicable methodology that transcends the mining sector and can be applied to others with similar constraints. However, some challenges in this research include reliance on published literature for the technology scoring. Future research in this area includes validating these findings through pilot projects at some of Afghanistan's mining sites, as well as applying the methodological framework to other sectors, such as agriculture and energy.

Acknowledgements

The authors sincerely thank Asst. Prof. M. Reza Hussaini for his valuable contribution to this research. Also, we are deeply grateful to all the faculty members, mining engineers, mine managers, specialists, and inspectors of the Afghanistan mining sector who generously donated their time and expertise to participate in this survey. Their practical knowledge and perspectives were essential in grounding this study in the realities of Afghanistan.

Author Contributions

- Zaman Nihzat: Conceptualization, methodology, software, formal analysis, research, data collection, writing of the main draft, and visualization.
- Aref Naimzad: Supervision, validation, writing, review, and editing.
- Fahim Weeyar: Supervision, writing - review, and editing.
- All authors reviewed and approved the final version.

References

Amalina, N. N., & Larasati, H. E. (2020). The Implementation of Contractor Safety Management System to Prevent Work Accidents at Coal Mining Company. *The Indonesian Journal Of Occupational Safety and Health*, *9*(3), 338. https://doi.org/10.20473/ijosh.v9i3.2020.338-348

Araujo, F., Taborda-Llano, I., Nunes, E., & Santos, R. (2022). Recycling and Reuse of Mine Tailings: A Review of Advancements and Their Implications. *Geosciences*, *12*(9), 319. https://doi.org/10.3390/geosciences12090319

Aziz, A., Schelén, O., & Bodin, U. (2020). A Study on Industrial IoT for the Mining Industry: Synthesized Architecture and Open Research Directions. *IoT*, *1*(2), 529–550. https://doi.org/10.3390/iot1020029

Bartoli, A. B., & Hernández-Ramírez, F. H.-R. (2023). The use of IoT technologies for advanced risk management in tailings dams. *XI International Conference on Adaptive Modeling and Simulation (ADMOS 2023), SEC4TD Mini-Symposium on Tailings Dams Modelling and Data Assimilation for Monitoring*. https://doi.org/10.23967/admos.2023.075

Battulwar, R., Winkelmaier, G., Valencia, J., Naghadehi, M. Z., Peik, B., Abbasi, B., Parvin, B., & Sattarvand, J. (2020). A Practical Methodology for Generating High-Resolution 3D Models of Open-Pit Slopes Using UAVs: Flight Path Planning and Optimization. *Remote Sensing*, *12*(14), 2283. https://doi.org/10.3390/rs12142283

Br Sembiring, B. S., Zarlis, M., Sawaluddin, Agusnady, A., & Qowidho, T. (2019). Comparison of SMART and SAW Methods in Decision Making. *Journal of Physics: Conference Series*, *1255*(1), 012095. https://doi.org/10.1088/1742-6596/1255/1/012095

Brown Requist, Kw., Lutz, E., & Momayez, M. (2024). Near real-time interpolative algorithm for modelling air quality in underground mines. *Journal of the Southern African Institute of Mining and Metallurgy*, *124*(3), 153–161. https://doi.org/10.17159/2411-9717/2638/2024

Cacciuttolo, C., & Atencio, E. (2023). Dry Stacking of Filtered Tailings for Large-Scale Production Rates over 100,000 Metric Tons per Day: Envisioning the Sustainable Future of Mine Tailings Storage Facilities. *Minerals*, *13*(11), 1445. https://doi.org/10.3390/min13111445

Cacciuttolo, C., Atencio, E., Komarizadehasl, S., & Lozano-Galant, J. A. (2025). Development of an Advanced Multi-Layer Digital Twin Conceptual Framework for Underground Mining. *Sensors*, *25*(21), 6650. https://doi.org/10.3390/s25216650

Cranford, R. (2023). Conceptual application of digital twins to meet ESG targets in the mining industry. *Frontiers in Industrial Engineering*, *1*, 1223989. https://doi.org/10.3389/fieng.2023.1223989

Daou, I. E., Harouna, S., Moustapha, S. C. M., Hassan, A. M., Amadou, A. H., & Zabre, B. M. (2022). Comparative Study between the Topographic Method (Classical) and Photogrammetric Method (by Drone) for the Monitoring and Data Acquisition of Mining Works: A Case of the SOMAÏR Uranium Mine, Arlit, North Niger. *Current Journal of Applied Science and Technology*, *41*(48), 109–122.

Deshmukh, R., Mileva, A., & Wu, G. C. (2018). Renewable energy alternatives to mega hydropower: A case study of Inga 3 for Southern Africa. *Environmental Research Letters*, *13*(6), 064020. https://doi.org/10.1088/1748-9326/aabf60

Dotsenko, E., Ezdina, N., Galiuta, O., & Cehlar, M. (2021). National Technology Initiative as a Platform for the Diffusion of Convergent Technologies in the Russian Mining

Industry. *E3S Web of Conferences*, *278*, 03014. https://doi.org/10.1051/e3sconf/202127803014

Ellabban, O., & Alassi, A. (2021). Optimal hybrid microgrid sizing framework for the mining industry with three case studies from Australia. *IET Renewable Power Generation*, *15*(2), 409–423. https://doi.org/10.1049/rpg2.12038

Feo, A. D., Mortazavi, S., Langley, S., Morin, L., Prabhakar, G., Demers, A., Bedard, I., & Volchek, K. (2020). The Effects of Water Recycling on Flotation at a North American Concentrator—Part 1. *Journal of Minerals and Materials Characterization and Engineering*, *08*(04), 240–276. https://doi.org/10.4236/jmmce.2020.84016

Forkuor, G., Ullmann, T., & Griesbeck, M. (2020). Mapping and Monitoring Small-Scale Mining Activities in Ghana using Sentinel-1 Time Series (2015–2019). *Remote Sensing*, *12*(6), 911. https://doi.org/10.3390/rs12060911

Grewar, T. (2019). South Africa's options for mineimpacted water reuse: A review. *Journal of the Southern African Institute of Mining and Metallurgy*, *119*(3). https://doi.org/10.17159/2411-9717/2019/v119n3a12

Gromov, E. (2020). Digital transformation of underground mining flow processes: Post-event analysis and world's experience. *Izvestiya Vysshikh Uchebnykh Zavedenii Gornyi Zhurnal*, *1*(8), 90–108. https://doi.org/10.21440/0536-1028-2020-8-90-108

Guntur Suryaning Hadi, Dyah Santhi Dewi, & Ratna Sari Dewi. (2023). Analyses of Critical Success Factors and Barriers to the Implementation of Indonesian Mining Safety Management System: Case Study of a Nickel Mine & Processing Company. *Jurnal Multidisiplin Madani*, *3*(6), 1321–1343. https://doi.org/10.55927/mudima.v3i6.3178

Hamraoui, L., Bergani, A., Ettoumi, M., Aboulaich, A., Taha, Y., Khalil, A., Neculita, C. M., & Benzaazoua, M. (2024). Towards a Circular Economy in the Mining Industry: Possible Solutions for Water Recovery through Advanced Mineral Tailings Dewatering. *Minerals*, *14*(3), 319. https://doi.org/10.3390/min14030319

Hazrathosseini, A., & Moradi Afrapoli, A. (2023). Maximizing Mining Operations: Unlocking the Crucial Role of Intelligent Fleet Management Systems in Surface Mining's Value Chain. *Mining*, *4*(1), 7–20. https://doi.org/10.3390/mining4010002

Kamran-Pishhesari, A., Moniri-Morad, A., & Sattarvand, J. (2024). Applications of 3D Reconstruction in Virtual Reality-Based Teleoperation: A Review in the Mining Industry. *Technologies*, *12*(3), 40. https://doi.org/10.3390/technologies12030040

Kim, S.-M., Choi, Y., & Suh, J. (2020). Applications of the Open-Source Hardware Arduino Platform in the Mining Industry: A Review. *Applied Sciences*, *10*(14), 5018. https://doi.org/10.3390/app10145018

Kumar, R., & Pamucar, D. (2025). A Comprehensive and Systematic Review of Multi-Criteria Decision-Making (MCDM) Methods to Solve Decision-Making Problems: Two Decades from 2004 to 2024. *Spectrum of Decision Making and Applications*, *2*(1), 177–196. https://doi.org/10.31181/sdmap21202524

Lee, S. (2020). Review on Characteristics and Monitoring of Particulate Matter Emitted from Mining Operation. *Journal of the Korean Society of Mineral and Energy Resources Engineers*, *57*(2), 234–242. https://doi.org/10.32390/ksmer.2020.57.2.234

Leung, R., Hill, A. J., & Melkumyan, A. (2025). Automation and AI Technology in Surface Mining With a Brief Introduction to Open-Pit Operations in the Pilbara. *IEEE Robotics & Automation Magazine*, *32*(3), 164–183. https://doi.org/10.1109/MRA.2023.3328457

Loginov, E., Ligotsky, D., & Argimbaev, K. (2020). Averaging the operating stripping ratio for sinking mining systems based on mathematical simulation. *Journal of Physics: Conference Series*, *1614*(1), 012050. https://doi.org/10.1088/1742-6596/1614/1/012050

Maest, A. (2023). Remining for Renewable Energy Metals: A Review of Characterization Needs, Resource Estimates, and Potential Environmental Effects. *Minerals*, *13*(11), 1454. https://doi.org/10.3390/min13111454

Mahir, O., Rochd, A., Benazzouz, A., & Ghennioui, H. (2024). Towards decarbonizing large-scale industries: A decision support framework for optimizing grid-connected PV-battery energy systems planning – Case study of an OCP mining site, Morocco, North Africa. *Heliyon*, *10*(20), e39075. https://doi.org/10.1016/j.heliyon.2024.e39075

Moomen, A.-W., Lacroix, P., Benvenuti, A., Planque, M., Piller, T., Davis, K., Miranda, M., Ibrahim, E., & Giuliani, G. (2022). Assessing the Applications of Earth Observation Data for Monitoring Artisanal and Small-Scale Gold Mining (ASGM) in Developing Countries. *Remote Sensing*, *14*(13), 2971. https://doi.org/10.3390/rs14132971

Moradi Afrapoli, A., Upadhyay, S. P., & Askari-Nasab, H. (2024). A nested multiple-objective optimization algorithm for managing production fleets in surface mines. *Engineering Optimization*, *56*(3), 378–391. https://doi.org/10.1080/0305215X.2022.2153840

Mugurusi, G., & Ahishakiye, E. (2022). Blockchain technology needs for sustainable mineral supply chains: A framework for responsible sourcing of Cobalt. *Procedia Computer Science*, *200*, 638–647. https://doi.org/10.1016/j.procs.2022.01.262

Nero, M. A. (2025). Sustainable Mining Management in Afghanistan: Challenges and Solution. *Journal of Natural Sciences – Kabul University*, *8*(2), 195–223. https://doi.org/10.62810/jns.v8i2.436

Nero, M. A., & Rahmani, A. B. (n.d.). *Mining Management in Afghanistan: Opportunities, Challenges, Constraints and Strategies for Correct Use of the Mineral Resources of the Country*.

Onifade, M., Adebisi, J. A., & Zvarivadza, T. (2024). Recent advances in blockchain technology: Prospects, applications and constraints in the minerals industry. *International Journal of Mining, Reclamation and Environment*, *38*(7), 497–533. https://doi.org/10.1080/17480930.2024.2319453

Pincheira, M., Antonini, M., & Vecchio, M. (2022). Integrating the IoT and Blockchain Technology for the Next Generation of Mining Inspection Systems. *Sensors*, *22*(3), 899. https://doi.org/10.3390/s22030899

Plessis, H. du, Grobler, H., & Mashimbye, C. (2022). A review of GISc education, its value and use in the mining and exploration industries. *South African Journal of Geomatics*, *11*(1). https://doi.org/10.4314/sajg.v11i1.9

Saleem, H. A., & Ayalew, A. T. (2025). Enhancing environmental sustainability and operational efficiency in a case study of limestone quarry in an arid climate. *Scientific Reports*, *15*(1), 18884. https://doi.org/10.1038/s41598-025-01230-9

Seraj, M., & Olaide, A. R. (2024). Assessing the Environmental Sustainability Corridor: Carbon Emissions in Relation to Gold Price, Economic Growth, Foreign Direct Investment, and Renewable Energy Consumption. *Standards*, *4*(4), 247–261. https://doi.org/10.3390/standards4040012

Shi, H., Xie, J., Wang, X., Li, J., & Ge, X. (2020). An operation optimization method of a fully mechanized coal mining face based on semi-physical virtual simulation. *International Journal of Coal Science & Technology*, *7*(1), 147–163. https://doi.org/10.1007/s40789-019-00282-3

Shvachych, G. G., Moroz, B. I., Pobochii, I. A., Timchenko, O. P., Kozenkova, V. D., & Busygin, V. V. (2022). Main mechanisms of blockchain technology implementation in digital technologies application. *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu*, (3), 168–172. https://doi.org/10.33271/nvngu/2022-3/168

Strzałkowski, P., Romańczukiewicz, K., Bęś, P., Delijewska, B., Sitarska, M., & Janiszewski, M. (2025). The Application of VR Technology in Engineering Issues: Geodesy and Geomatics, Mining, Environmental Protection and Occupational Safety. *Sensors*, *25*(22), 6848. https://doi.org/10.3390/s25226848

Tang, K. H. D. (2024). Artificial Intelligence in Occupational Health and Safety Risk Management of Construction, Mining, and Oil and Gas Sectors: Advances and Prospects. *Journal of Engineering Research and Reports*, *26*(6), 241–253. https://doi.org/10.9734/jerr/2024/v26i61177

Torbacki, W. (2025). An Integrated MCDA Framework for Prioritising Emerging Technologies in the Transition from Industry 4.0 to Industry 5.0. *Applied Sciences*, *15*(15), 8168. https://doi.org/10.3390/app15158168

Torres, V. F. N., Mateus, G. R., Martins, A. G., Carneiro, W., & Chaves, L. S. (2020). Integrated optimization and simulation models for short-term open-pit mine planning. *Journal of the Southern African Institute of Mining and Metallurgy*, *120*(11). https://doi.org/10.17159/2411-9717/1266/2020

Tripathi, A. K., Aruna, M., Parida, S., Nandan, D., Elumalai, P. V., Prakash, E., Isaac JoshuaRamesh Lalvani, J. S. C., & Rao, K. S. (2024). Integrated smart dust monitoring and prediction system for surface mine sites using IoT and machine learning techniques. *Scientific Reports*, *14*(1), 7587. https://doi.org/10.1038/s41598-024-58021-x

Vangu, G. M., Croitoru, A., Mitrache, M., & Dima, N. (2023). Design of a GIS Database for Surface Mining. *Journal of Applied Engineering Sciences*, *13*(2), 289–296. https://doi.org/10.2478/jaes-2023-0037

Wang, H., Tan, L., Zhang, Y., Gong, Q., Zhang, S., Ren, Y., & He, T. (2023). A Management Specification for Data Sharing Security in the System Construction of Smart Mine. *Security and Communication Networks*, *2023*, 1–13. https://doi.org/10.1155/2023/1414530

Xia, Z., Tan, Z., Qi, K., & Li, W. (2018). Design of material management system of mining group based on Hadoop. *IOP Conference Series: Earth and Environmental Science*, *108*, 042052. https://doi.org/10.1088/1755-1315/108/4/042052

Yaghini, A., Hall, R., & Apel, D. (2022). Autonomous and Operator-Assisted Electric Rope Shovel Performance Study. *Mining*, *2*(4), 699–711. https://doi.org/10.3390/mining2040038

Yang, C.-H., & Müterthies, A. (2020). Introduction of Integrated Mining Impact Monitoring – i^{2}Mon Development Project. *Proceedings of IAHS*, *382*, 225–229. https://doi.org/10.5194/piahs-382-225-2020

Zhang, Y., & Li, G. (2020). Open Pit Mining Process Optimization Decision System Based on Artificial Intelligence Technology. *Journal of Physics: Conference Series*, *1648*(4), 042056. https://doi.org/10.1088/1742-6596/1648/4/042056

Zhironkina, O., & Zhironkin, S. (2023). Technological and Intellectual Transition to Mining 4.0: A Review. *Energies*, *16*(3), 1427. https://doi.org/10.3390/en16031427

Zhou, C., Damiano, N., Whisner, B., & Reyes, M. (2017). Industrial Internet of Things. *Mining Engineering*, *69*(12), 50–56. https://doi.org/10.19150/me.7919

Zhou, L., Cao, Q., Yu, K., Wang, L., & Wang, H. (2018). Research on Occupational Safety, Health Management and Risk Control Technology in Coal Mines. *International Journal of Environmental Research and Public Health*, *15*(5), 868. https://doi.org/10.3390/ijerph15050868

Zhu, W., Kang, J., Zhang, D., Sun, W., Gao, Z., Han, H., & Liu, R. (2024). Treatment and Recycling of Tungsten Beneficiation Wastewater: A Review. *Separations*, *11*(10), 298. https://doi.org/10.3390/separations11100298

Ziętek, B., Banasiewicz, A., Zimroz, R., Szrek, J., & Gola, S. (2020). A Portable Environmental Data-Monitoring System for Air Hazard Evaluation in Deep Underground Mines. *Energies*, *13*(23), 6331. https://doi.org/10.3390/en13236331

Zvarivadza, T., Onifade, M., Dayo-Olupona, O., Said, K. O., Githiria, J. M., Genc, B., & Celik, T. (2024). On the impact of Industrial Internet of Things (IIoT)—Mining sector perspectives. *International Journal of Mining, Reclamation and Environment*, *38*(10), 771–809. https://doi.org/10.1080/17480930.2024.2347131