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SAFE MINING OPERATION THROUGH TECHNOLOGICAL ADVANCEMENT IN SOUTH ASIAN COAL MINES: A CRITICAL REVIEW

MOHAMMAD FORRUKH HOSSAIN KHAN*, LABIBA AKTER
SAIMUN ISLAM TANMOY, MD. SOHAN MIAH
AND FAYSAL AHMED AKASH

Mine Planning and Design Laboratory, Department of Petroleum and Mining Engineering, Jashore University of Science and Technology, Jashore-7408, Bangladesh

Abstract

Nations in South Asia, such as India, Pakistan, Bangladesh, and Afghanistan, are undergoing economic development, with coal mining serving as a critical sector. Modernization and enhanced safety measures can significantly boost the benefits derived from coal mining. This review assesses the current state of coal mine safety across the region, emphasizing persistent challenges such as outdated technologies, weak regulatory enforcement, and limited workforce training. Drawing on recent incidents and case studies, it identifies major hazards including roof collapses, gas explosions, spontaneous combustion, and subsidence. The study also explores the invention and implementation of AI-based smart caps, whose integrated sensors have helped reduce mining accidents by approximately 70%. Furthermore, it highlights the potential of adopting advanced technologies such as the Internet of Things (IoT), LoRa communication systems, real-time monitoring, Artificial Intelligence (AI), and virtual reality-based training programs. Sustainable practices like dense stowing and integrated safety systems are also examined to address ecological concerns. By comparing international best practices with regional applications, the review proposes a practical, technology-driven, and policy-supported roadmap aimed at enhancing both the safety and sustainability of coal mining in South Asia.

Key words: Coal mine safety, Mine hazards, IoT in mining, LoRa communication in mines, AI monitoring

Introduction

Underground coal mines are particularly known for their elevated risk levels and frequent accident rates (Saleh and Cummings, 2011). Mining continues to be one of the most hazardous occupations. Coal miners face high risks that can lead to serious fatalities, resulting in high human and economic costs. While risks can be reduced through safety

*Corresponding author: E-mail: dr.forrukh@just.edu.bd

measures, their complete exclusion is not possible due to the inherently hazardous nature of work (Tripathy and Ala, 2018). Mine accidents typically result from a combination of factors such as human error, equipment failure, environmental and management issues, and hidden production hazards. These accidents often follow an evolution process, beginning with inherent mining risks, which, if not effectively controlled, develop into safety hazards and ultimately lead to accidents when corrective measures fail (Su and Hu, 2024). This progression is effectively illustrated in Figure 1, which shows how initial coal mine safety risk factors contribute to specific hidden dangers and how these, in turn, lead to various types of accidents, emphasizing the cascading nature of safety failures in underground coal mining.

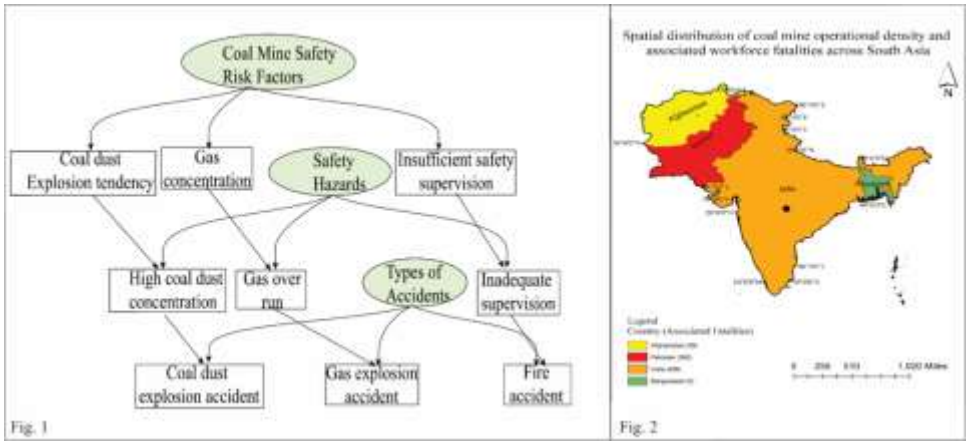


Fig. 1. Coal mine safety risk factors connecting with hazards and accidents (Su and Hu, 2024) and

Fig. 2. Spatial distribution of coal mine operational density and associated workforce fatalities across South Asia.

Given the severity and persistence of these dangers, governments and industry bodies have recognized the urgent need for systematic interventions to mitigate risks and safeguard workers. In South Asian countries, mine authorities implement safety measures, but the enforcement and effectiveness of these measures vary significantly across regions. Coal mining accidents in South Asia affect not only workers but also the families and communities that depend on mining for their livelihoods. In countries such as Bangladesh, India, Pakistan, and Afghanistan, many underground miners come from low-income households where coal mining is the main source of income. When accidents occur, families often lose their only wage earner, forcing them into financial hardship,

debt, and insecure informal work (Jiskani *et al*., 2020; Monir and Hossain, 2012) .Coal mining accidents and their associated hazards jeopardize local livelihoods by degrading ecosystems, diminishing agricultural productivity, and exacerbating the economic fragility of surrounding communities (Reza *et al*., 2024). In India, the households residing in active coal mining zones, including the Talcher Coalfield, experience heightened vulnerability across natural, health, and financial dimensions when compared with communities located outside mining areas (Sahoo and Senapati, 2021). Similarly, Pakistan's Cherat coalfield demonstrates that although coal mining generates employment opportunities, it simultaneously imposes substantial social and environmental costs, such as adverse health outcomes for workers, degradation of local water resources, and repeated mining accidents, all of which collectively hinder community well-being and sustainable economic development (Shah *et al*., 2019). These socio economic losses show the urgent need to improve mine safety. Strong enforcement of safety laws and regular inspections increase compliance and accountability. Improving safety is not only a technical requirement but a necessary step to protect livelihoods, sustain productivity, and support long-term regional development. In Bangladesh, coal mining at the Barapukuria Coal Mine faces serious safety, and environmental problems. These include groundwater level decline and water pollution, soil contamination from mine water and heavy metals, and land subsidence that damages nearby homes and farmland (Zahan *et al*., 2025). In Afghanistan, coal mining is, for the most part, informal and small-scale. The use of primitive extraction methods and the absence of regulatory oversight lead to frequent tunnel failures, chronic respiratory hazards, and a high incidence of mine fires (Wnuk, 2024). Reports on mining management in Afghanistan identify gaps in technical expertise, planning, supervision, and institutional capacity within the Ministry of Mines and Petroleum. These limitations reduce effective enforcement of regulations and weaken safety oversight, which allows unsafe mining practices to continue (Nero *et al*., 2022). In contrast, modern approaches such as the AHP–GA (Analytic Hierarchy Process–Genetic Algorithm) framework have been proposed to systematically identify, evaluate, and rank accident causative factors, thereby enabling the authorities of the Barapukuria Coal Mine to prioritize safety interventions and optimize resource allocation (Ahmed *et al*., 2021). Coal mining involves various inherent, operational, and occupational hazards, making safety a top priority for coal companies. To address these risks, companies follow a clear safety policy at the core of their operations. Globally, coal mining is a highly regulated industry. In India, coal mine safety laws form one of the most comprehensive frameworks to ensure occupational health and safety (Ministry of Coal, 2020). Bangladesh also shares the primary mining law, the Mines Act of 1923, with India from the colonial era. It was minimally adapted in

2005. Subsequently, the Mines and Mineral Resources (Control and Development) Act replaced the 1967 Act in 1992 (Hydrocarbon Unit, 2013). In a comparable manner, in Pakistan, the Constitution addresses the safety, welfare, and health of mine workers, while the Mines Act of 1923 and its associated rules provide a broader regulatory framework for mine safety. Additionally, this framework governs the granting, administration, and regulation of mining rights under the Regulation of Mines and Oilfields and Mineral Development (Federal Control) Act of 1948 and the rules made thereunder (Jiskani *et al*., 2019). Alongside these legal developments, studies and technological innovations in South Asia during recent times have increasingly focused on making underground coal mining safer with new methodologies and data-driven approaches.

While there is a lot of research on mine safety in countries like China, the U.S., and Australia, there is a clear lack of studies focusing on the specific safety issues in South Asian coal mines, especially in Bangladesh, India, Pakistan, and Afghanistan. This paper looks at the coal mining sector in this region, detailing its history and current risks. These risks include coal combustion, roof instability, poor ventilation, and ground subsidence. It also examines the social effects and points out gaps in miner welfare and the use of modern safety technologies. The study examines how innovations such as IoT monitoring, LoRa communication, AI, and VR training can enhance safety and efficiency. Drawing on global best practices and regional case studies, it provides a practical plan for enhancing mine safety and sustainability in South Asia.

Background and regional context

South Asian countries have different coal reserves, coal usage, and mining issues. The main countries with underground coal mines are Bangladesh, India, Pakistan, and Afghanistan. India runs 1,030 coal mines (Global Energy Monitor, 2025) and has approximately 378.21 billion tonnes of reserves (Ministry of Coal, 2023a). This makes India the world’s second-largest producer and importer of thermal coal. Coal provides about 55% of India's energy needs and produces over 70% of its electricity (Wang *et al*., 2023). Coal India Limited employs methods like Longwall and Room-and-Pillar mining for safe and effective extraction (Ministry of Coal, 2023b).). Mining has been a part of India’s industry since 1774. India now ranks just behind China in both production and consumption (Ministry of Coal, 2025). Bangladesh has five known coalfields, but only the Barapukuria mine in Dinajpur is active, with reserves of about 410 million tonnes (Hossain *et al*., 2014; Hydrocarbon Unit, 2024). Pakistan has around 185 billion tonnes

of coal, mostly found in the Thar coalfield (ZAREA, 2025). Mines in Balochistan, Punjab, and Sindh use methods like Longwall, Longwall Top Coal Caving (LTCC), and Room-and-Pillar (Uddin, 2021; Ullah et al., 2018). In Pakistan, underground coal mining uses a range of techniques, but the Room-and-Pillar method and the Longwall system are the most commonly applied. These approaches are mainly practiced in the coal-rich areas of Balochistan, Punjab, and Sindh (Ullah *et al.*, 2018). Afghanistan's mining is small-scale and outdated, with about 1.3 billion tonnes of reserves located mainly in the north. Key mines include Shabashak, Dehne Tor, and Lilav Qara Naver (Jamal and Khatami, 2023). In Figure 2, it shows the high fatality-to-mine ratio in regions like Pakistan and India underscores the critical gap in safety enforcement and technological adoption.

Safety hazards in coal mines

In Pakistan, India, and Afghanistan, miners face deadly hazards like collapsing roofs, gas explosions, fires, and unregulated rat-hole mining. Pakistan's safety standards lag decades behind countries like China, India, and Turkey, with underground operations especially dangerous due to unstable roofs, narrow tunnels, unsafe material handling, and frequent fires and explosions (Rehman *et al*., 2020). Between 2020 and 2024, Indian coal mines recorded 195 fatal accidents, resulting in 226 deaths (Factly, 2025). Poor ventilation in coal mines results in the accumulation of flammable gases, thereby increasing the risk of gas explosions. Insufficient ventilation also hinders effective heat dissipation and continuously supplies oxygen to residual coal, which promotes low-temperature oxidation, heat buildup, and ultimately, spontaneous combustion (Yuan and Smith, 2012; Zhang *et al*., 2021). In Bangladesh, the Barapukuria Coal Mine experiences significant safety challenges, exacerbated by hazardous underground conditions, particularly in goaf and sealed areas. Poorly regulated or insufficient airflow allows oxidation heat to exceed convective heat removal, which accelerates the self-heating process (Li *et al*., 2023; Yang *et al*., 2021). Roof falls are frequently attributed to unfavorable geological conditions, water-induced damage to surrounding rocks, and inadequate support and safety management (Wang *et al*., 2022). Shah *et al.* (2020) identified a direct correlation between production targets and coal mine fatalities. In the Cherat coalfield, prioritizing output over safety procedures increases the probability of human error. When such errors coincide with geological weaknesses and substandard mechanical conditions, the result is a heightened risk of severe accidents and system failures (Shah *et al.*, 2020). An examination of historical accident records, therefore, provides critical insight into how such technical and managerial deficiencies manifest in real-world mining disasters. In this context, Table 1 summarizes major coal mining

accidents in Pakistan, Afghanistan, Bangladesh, and India, highlighting their human toll and underlying causes.

Table 1. Major Coal Mining Accidents in South Asia.

Country	Date	Number of deaths	Cause of the accidents	Reference
Pakistan	March 20, 2011	52	Mine Collapse	
	February 9, 2015	19	Mine Collapse	(Shahani *et al*., 2021)
	August 2018	18	Mine Collapse	
	January 12, 2020	02	Mine collapse	
	January 21, 2020	02	Gas Explosion	(IndustriALL, 2020)
	January 27, 2020	01	Hit by a coal trolley	
	March 12, 2021	06	Explosion in Coal Mine	(Aljazeera, 2021)
Afghanistan	June 9, 2020	16	Dust explosion	(Dust Safety Science, 2020)
	February 3, 2022	10	Mine collapse	(World, 2022)
	May 23, 2023	04	Gas Explosion	(myRepublica, 2023)
Bangladesh	September 17, 2007	01	Struck by a road header	
	28 September 2008	01	Electrocution	(Monir and Hossain, 2012)
	May 11, 2010	01	Severe Roof Fall	
India	December 13, 2018	15	Flood in a 370-foot-deep rat hole mine due to breaching water filled shaft	(Indiatimes, 2018)

In Figure 3, the graph clarifies coal mine fatalities from 2011 to 2020 in China, India, and Russia, highlighting stark differences in accident rates among these countries. China, which possesses the largest number of coal mines globally, reported the highest fatalities throughout the decade, starting from 1,973 deaths in 2011 and declining to 225 in 2020. This high fatality rate is directly proportional to the vast scale of coal mining operations in China, which exposes more workers to risk (Wang *et al.*, 2023). The decline in mining fatalities over time shows ongoing efforts to improve safety through policy changes and technology. India has more coal mines than Russia and is the second-largest coal producer, yet it reports fewer fatalities, ranging from 18 to 94 each year. This indicates better ventilation, real-time monitoring, and mechanized systems. Russia, which has the smallest mining sector among the three countries, has the lowest fatality rates. This suggests it effectively enforces safety rules. Although data for other South Asian countries is limited, India serves as a useful reference for regional progress. Overall,

these findings indicate that, besides industry size, technology upgrades and strong regulations are crucial for reducing mining fatalities.

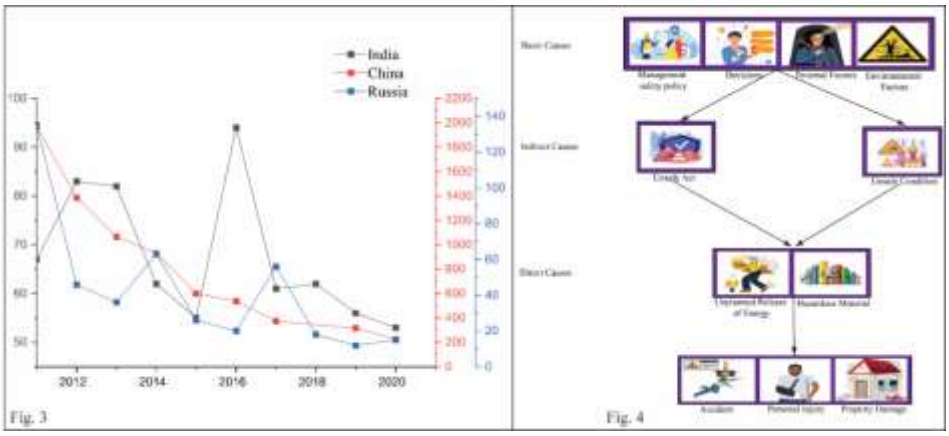


Fig. 3. Number of deaths of coal mine accidents in India, China, and Russia (2011-2020) (Ministry of Labor and Employment, 2025; Wang *et al.*, 2023) and

Fig. 4. Classification of Direct, Indirect, and Root Causes of Mining Accidents (Onifade, 2021).

China has a larger number of coal mines compared to other countries, which contributes to a higher occurrence of mining accidents due to increased exposure and operational scale. Between 2017 and 2021, China significantly reduced its coal mine fatality rate from 0.106 to 0.044 deaths per million tonnes, reflecting strong safety reforms and technological adoption (Zhang *et al*., 2023). China has significantly lowered its coal mine fatality rate through a multifaceted approach combining regulatory reinforcement, technological innovation, and structural reform. The jurisdictional consolidation of mining oversight, most notably via the establishment and empowerment of the National Mine Safety Administration and vertical supervision systems, has enhanced enforcement capabilities (Shi, 2013). India's rate has remained relatively stable at around 0.19 fatality rate per thousand persons from 2011-2021 (Ministry of Labor and Employment, 2025). In contrast, Pakistan shows a much higher risk, with a study of 2020 reporting 312 fatalities across 53 incidents between 2010 and 2018, with 51% caused by mine collapses (Shahani *et al*., 2020). The stark difference highlights China's progress in safety management, India's moderate stability, and Pakistan's urgent need for regulatory and infrastructural improvements.

Key safety challenges

Roof stability: Roof support systems in Pakistan's Eastern Salt Range coal mines are old and unsafe, leading to frequent accidents and reduced productivity. Timber, mainly Eucalyptus camaldulensis, is the most commonly used support material, along with some masonry walls and iron horseshoe supports. However, these supports are often installed without properly checking ground conditions or rock pressure, making them unreliable. Poor ventilation, moisture, and long-term wear weaken the timber, increasing the risk of roof and wall collapses. These collapses are a major cause of injuries and deaths. Eucalyptus is widely used because it grows quickly, is easily available, and is cheap, but it decays easily due to its low resin content (Khan and Emad, 2019). A study based on six years of fatal accident data from 292 Indian coal mines used a log-linear model to estimate potential fatalities (PF), relative risk of fatalities (RRF), and the effectiveness of safety measures (SME). The findings reveal that although accidents tend to occur more frequently near the mining face, remote areas with fewer workers, often overlooked in safety planning, pose a higher relative risk (Maiti and Khanzode, 2009).

Coal combustion: From December 2013 to July 2014, coal samples and underground atmospheric data from Barapukuria Coal Mine were analyzed using standard methods to assess spontaneous combustion risk. The results indicated moderate combustion liability, with certain Longwall areas showing high oxidation, and medium combustion risk (Ahamed *et al*., 2016). Spontaneous combustion (auto-oxidation) is a major cause of mine fires in Indian underground coal mines. Fires typically originate endogenously without external heat, when coal reacts with oxygen, producing heat that can lead to ignition. Coalfields like Jharia, Raniganj, Bokaro, Talcher, Chirimiri, etc., show ongoing issues with spontaneous combustion (Nimaje and Tripathy, 2015). A spontaneous combustion took place in coal face 1110 in Barapukuria coal mine in September 2005. In consequence, the face was closed and sealed with all the coal-cutting instruments worth millions of dollars (Kabir and Imam, 2013).

Mine ventilation: The Ventilation system in a mine sends fresh air through the mine to remove methane gas. Harmful emissions from mining operations are on the rise, making it increasingly difficult for mining companies to supply adequate ventilation to active work areas (Shriwas and Pritchard, 2020). Poor ventilation can lead to dangerous gas buildup. This was evident in the Xiaojiawan disaster in Sichuan Province on August 29, 2012. A severe gas explosion there claimed 45 lives (Xianfei *et al*., 2018). The main cause of the explosion is methane, a colorless, odorless, highly flammable gas that can displace oxygen, and cause miners to asphyxiate (MINETEK, 2024). Effective

ventilation involves overcoming challenges like controlling airflow resistance, preventing leaks, and adjusting to changing mine conditions. It also requires ensuring air quality in tight spaces (Heriyadi and Zakri, 2021).

Subsidence: Mine subsidence endangers workers, damages infrastructure, and may cause mine collapse. The subsidence prediction methods include GPR, seismic surveys, geodetic monitoring, LiDAR, aerial photography, satellite imagery, and In-SAR. However, not all of these methods are cost-effective for South Asia (Behera and Rawat, 2023). In China, mitigation strategies involve backfill mining for stability, strip mining to leave support pillars, grouting reinforcement to strengthen the rock layers, and partial mining with filling to balance safety and extraction. Integrated methods provide customized solutions but come with high costs, the need for real-time monitoring, and technical expertise (Chen *et al*., 2016).

Miner safety concern: In Cherat, District Nowshera (KPK) many coal mine workers face musculoskeletal problems. A staggering 76.64% of these cases are linked to inadequate training. This highlights a serious gap in safety management since traditional monitoring is favored over practical, skill-based instruction. Experts stress that hands-on training, live demonstrations, and ongoing education are much more effective at preventing injuries (Asif, 2017). Mining accidents occur due to a mix of direct causes, such as hazardous energy release or toxic exposure, and indirect causes, like unsafe actions, fatigue, or equipment failures. Basic causes also play a role, including poor management and environmental factors. As shown in Figure 4, these elements can come together to trigger accidents by causing the unplanned release of dangerous energy or materials. It is crucial to tackle all levels for effective prevention (Onifade, 2021).

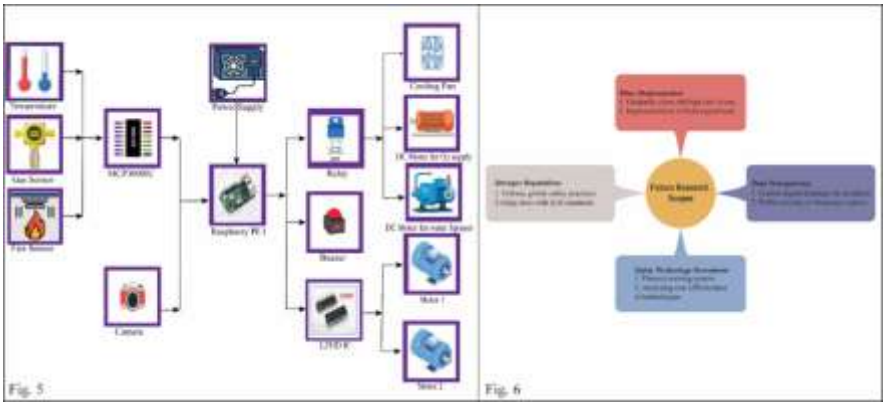


Fig. 5. Block diagram of Transmitter (Onifade *et al*., 2023) and
Fig. 6. Future Research Priorities for Safer Mining Practices.

Limited accountability, economic pressures, tolerance of unsafe practices, and weak emergency response systems also increase risks. Without modern equipment, proper monitoring tools, and consistent enforcement, coal miners remain at risk of preventable accidents and long-term health issues (Wang *et al*., 2019; Wang and Li, 2020).

Technological advancements

Underground coal mining in South Asia uses methods like Longwall, Room-and-pillar, and LTCC. These methods are chosen based on geological conditions but often face challenges due to limited mechanization and weak safety protocols. Although these methods improve subsidence control and ventilation, unexpected geology can still cause equipment failures and technological hazards (Ali and Pal, 2022; Jabin *et al*., 2013; Vinay *et al*., 2022). Therefore, to reduce such risks and ensure safer mining operations, the continuous mining method is increasingly considered a better alternative, as it uses a single continuous miner to cut and load coal simultaneously. This change improves safety, increases productivity, and removes the need for drilling and blasting by using a rotating drum with cutting bits (Indian Mine Manager Association, 2023).

LoRa communication: LoRa (Long Range) technology is a low-power and cost-effective option for real-time safety monitoring in underground coal mines. It is suitable for budget-limited regions like South Asia. LoRa can transmit sensor data such as gas levels, temperature, and humidity over long distances with less interference, even in blocked underground areas. This helps in early hazard detection (Kumar *et al*., 2023). A standard LoRa system uses a Raspberry Pi-based transmitter to gather data from sensors. These include the LM35 for temperature and gas sensors for CH_4, CO, CO_2, and fire detection. It also controls devices like fans, motors, and servos (Figure 5). Data is sent to a control room PC for display and can be accessed through a web interface, using Python for control and expert monitoring (Ram *et al*., 2018).

Additional technologies improve safety even more. VR-based training immerses miners in simulated hazardous situations, enhancing their preparedness and response skills without real-world risk (Grabowski and Jankowski, 2015). Remote operation systems, ranging from LOS (Light-of-sight) controllers (100–500 m) to semi-autonomous tele-remote units, enable safe, centralized control of mining vehicles. This improves flexibility and reduces exposure to danger (Onifade *et al.*, 2023).

Although LoRa has many benefits, its use in South Asian underground coal mines is challenging because complex tunnel layouts, moisture, and metallic structures can weaken signals and reduce communication reliability (Kumar *et al.*, 2023; Scalambrin *et*

al., 2023). Unstable power supply and lack of technical skills can reduce system performance, especially in older mines. Also, when many devices are connected, the network may become overloaded, causing delays and data loss (Gaitán *et al*., 2022). These problems can be solved with solutions suitable for the area. Placing nodes or mesh-based LoRa networks along tunnels and intersections can make the signal stronger and more reliable (Musonda *et al*., 2024). Kelechi *et al*. (2025) showed that underground IoT and LoRa devices can be powered using wireless energy transfer and energy harvesting. Radio Frequency energy is sent to receivers and stored in supercapacitors to run sensors, reducing reliance on batteries and solving power supply issues in mines (Kelechi *et al.*, 2025).

Internet of Things: IoT technologies improve safety in underground coal mines by enabling real-time monitoring of environmental and operational conditions. However, implementing these systems is more difficult than in surface mines. The Mine IoT (MIoT) system has a three-layer structure: perception and control, network, and application layers. This setup helps to detect hazards and transmit data, but more research is needed for better frameworks and data management (Zhang *et al*., 2023). Practical uses include smart safety helmets that have sensors to detect methane, carbon monoxide, temperature, and humidity. They also come with accelerometers to register head impacts and confirm helmet use. These helmets connect to central control units using wireless protocols like Wi-Fi, Bluetooth, ZigBee, or LoRaWAN. This ensures low power consumption, flexible deployment, and reliable data transfer (Ghadyani *et al*., 2021; Kartik and Manimaran, 2023). More advanced IoT-based systems combine wearable devices like smart bracelets and miner lamps. These devices track vital signs, detect hazardous gases, monitor fatigue, and determine location using UWB technology. Data is sent through low-latency 5G and UWB networks. A neural network model estimates fatigue based on saliva pH. This information is displayed on a central monitoring platform, allowing for quick emergency responses. Successfully deployed in a Chinese coal mine without accidents, the system plans to upgrade with GNSS tracking and blockchain for added security (Jiang *et al*., 2024).

Artificial Intelligence: AI technologies, including neural networks and deep learning models, can predict mining hazards such as rock falls and gas leaks with over 90% accuracy (Yu *et al*., 2024). Since it is impractical to install sensors in every tunnel, AI tools like genetic algorithms, reinforcement learning, and machine learning models help improve ventilation. They do this by predicting airflow, calculating resistance, detecting faults, and ensuring system reliability. Methods such as Genetic Algorithms (GA), Support Vector Machines (SVM), Neural Networks (MLP, KNN), Fuzzy Logic, and

Monte Carlo simulations allow for precise analysis and management of underground ventilation systems (Semin and Kormshchikov, 2024). For gas monitoring, models like TCN-TimeGAN and improved LSTM analyze real-time location and airflow data. They track changes over time and detect sudden spikes, which reduces explosion risks (Zhang, 2025). AI is also used in safety wearables, such as BHP's smart caps in Chilean mines. These caps use brainwave sensors to detect driver fatigue and send alerts to both operators and supervisors, leading to a 70% reduction in serious accidents (Softeq, 2022).

Table 2 compares advanced safety technologies based on hazard detection, cost, scalability in South Asia, and limitations. It helps identify the most practical and effective options for improving mine safety in the region (Kumar *et al.*, 2023).

Table 2. Performance and Applicability of Smart Safety Technologies in South Asian Underground Mines (AI Programmers, 2025; Devum, 2024; Kumar *et al.*, 2023; Santos *et al.*, 2022; Wu and Liebeherr, 2023).

Technology	Effectiveness	Cost estimate (USD)	Scalability in South Asia	Limitations
LoRA communication	Detects gas early and transmits data wirelessly across long distances	~$20–$50 per node	Medium	Needs regular maintenance and performance may drop with more devices
IoT monitoring	Monitors gases, pressure, temperature, and humidity also easy to expand	~$50.00	Medium-High	Requires skilled maintenance and potential signal interference
AI monitoring	Detects anomalies, gives early warnings, and supports data analysis & visuals	~$10,000-$50,000	Low-High	Costly and integration with older system is difficult

Mollah *et al*. (2025) reported that Bangladesh has begun to explore IoT-based safety and monitoring systems in coal mines. These systems utilize environmental sensors to detect hazardous conditions, such as gas leaks, high temperatures, and humidity changes, enabling the identification of hazards in real-time and the issuance of early warnings (Mollah *et al.*, 2025). In India, Nagarnaik (2025) have proposed IoT-based monitoring, and alert frameworks leveraging wireless sensor networks for environmental surveillance, and miner safety, reflecting a growing academic focus on real-time, sensor-driven safety technologies (Nagarnaik, 2025). However, most of these initiatives exist only as ideas, prototypes, or project plans, and very few have been tested in real mines or small-scale pilot projects. As a result, the performance of these technologies in real mining conditions is still not well proven. As Afghanistan and Pakistan lack sufficient research

on the real-world deployment of these technologies, further applied studies, and large-scale pilot projects are urgently needed to ensure integration with established mine safety management practices.

Risk management strategies and policy: Accidents still happen in mines, even with safety measures in place. This makes strong emergency preparation crucial. Mines need clear disaster plans, rescue rooms, stations, and trained response teams (Indian Mine Manager Association, 2023). In China, safety in underground engineering has improved through laws, safety systems, technology, and accident forecasting. Still, issues like unsafe behavior, lack of innovation, and poor regulations persist (Qian and Lin, 2016). Fuzzy logic helps manage mining risks by turning uncertain data, like gas pressure or rock strength, into straightforward categories such as "low" or "high." This leads to better safety decisions (Slashchova *et al*., 2023). Fuzzy Fault Tree Analysis (FFTA) uses this method to pinpoint key causes of gas explosions. It shows that isolating gas and ignition sources, along with better detection, significantly lowers risks (Shi *et al*., 2018).

Sustainable solution in coal mine safety

Sustainable mining seeks to minimize environmental damage both during and after mining operations, while also promoting long-term land use for purposes such as grazing, wildlife conservation, or renewable energy production (Chugh *et al*., 2023). In India, the adoption of technology-driven methods, including efficient power generation, planned coal washing, and coordinated mining, has contributed to reduced emissions and waste. Additional practices, such as effective mine closures, land rehabilitation, water treatment, dust control, and the use of renewable energy for methane capture, further support environmental objectives (Paliwal *et al*., 2021). In Pakistan, a people-focused approach emphasizes structured safety systems, modern tools like gas detectors and real-time monitoring, worker training, clear emergency plans, community engagement, and updated policies. This is strengthened by regular inspections and strict enforcement (Jiskani et al., 2020). On a global scale, sustainable coal mining must balance environmental protection, technological innovation, and evolving energy demands. Major challenges include minimizing environmental impacts, and unmanned technologies, and redefining the role of coal in conjunction with renewable energy sources (Zhironkin and Cehlár, 2021). Advanced systems, such as continuous miner-bolter machines, RFID worker tracking, and wireless structural and gas sensors, improve safety and productivity (Sahu *et al*., 2015). Innovations like solid dense stowing, automating, and sync mining with goaf support. It may improve safety, stability, and efficiency while cutting waste and

pollution from dump fires. This mechanized approach offers a more sustainable alternative to traditional methods, as seen in countries like China (Huang *et al*., 2017).

Future Recommendations

Figure 6 highlights the future research scopes that can contribute to improving mine safety and supporting modernization in the mining industry. To successfully implement these future improvements, strong regional cooperation and policy-level support are essential, especially in South Asia. In this context, regional organizations can play a significant role in establishing a unified safety framework. The SEC (SAARC Energy Centre) seeks to address increasing regional energy demand by fostering cooperation in shared resource management, policy harmonization, and coordinated infrastructure development to ensure affordable and sustainable energy for all SAARC member states (SAARC Energy Centre, 2024). Within this framework, the SEC may support the establishment of the South Asian Mining Safety Regulatory Body (SAMSRB) by offering an institutional platform under the SAARC framework, advancing regional policy harmonization on mining safety, and incorporating mine safety considerations into energy planning. Implementing the SAMSRB may be difficult in less developed mining regions such as Afghanistan and parts of Pakistan. Weak institutions, limited law enforcement, inadequate infrastructure, security issues, and a shortage of skilled personnel hinder effective safety governance. Informal mining, low data transparency, and financial constraints may also delay the adoption of harmonized regional safety standards (DeWitt *et al*., 2021; Khan *et al*., 2024). Phased implementation, accompanied by capacity building and technical training programs, should be prioritized to address these challenges. Additionally, the development of regional financial and technical support mechanisms is necessary to strengthen regulatory institutions and enhance compliance with safety standards.

Conclusion

The coal mining sector in South Asia faces persistent safety challenges, exacerbated by outdated infrastructure and inadequate regulatory enforcement. This review focuses on underground mines in India, Pakistan, Bangladesh, and Afghanistan, and evaluates the potential of cost-effective technologies to address these issues. Technologies such as LoRa communication, Internet of Things (IoT) monitoring, artificial intelligence (AI) for risk prediction, and virtual reality (VR) safety training offer significant opportunities to enhance safety. However, meaningful improvement requires integrating these

technologies with sustainable mining practices. Such an approach is essential to maintain the long-term acceptability and viability of coal mining in the region.

Declaration of competing interest

The authors declare that there are no financial or personal relationships that may have influenced the work presented in this paper.

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