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Research Article

Risk Mapping and Comprehensive Safety Analysis in The Indian Mining Industry

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Abstract

The mining industry operates within highly dynamic and hazardous environments where geological uncertainty, operational complexity, and human factors significantly elevate occupational risks. Effective risk identification and mitigation are therefore essential for ensuring sustainable mining operations and worker safety. This study presents a comprehensive framework for risk mapping and safety analysis in the Indian mining industry using qualitative, semi-quantitative, and quantitative risk assessment approaches. Hazard categories including geological, mechanical, environmental, and human-related risks were systematically evaluated using a risk matrix model based on likelihood and consequence analysis. The study identified roof falls and machinery failures as extreme-risk events demanding immediate intervention. Historical accident data from the Directorate General of Mines Safety (DGMS) between 2016 and 2022 indicate a gradual decline in fatality rates due to strengthened regulatory enforcement and improved technological adoption. The findings further demonstrate that the integration of Internet of Things (IoT)-based monitoring systems, artificial intelligence (AI), and GIS-enabled risk mapping substantially enhances hazard prediction and operational safety. The paper concludes with strategic recommendations emphasizing engineering controls, safety culture development, predictive analytics, and technological modernization for achieving sustainable and safer mining practices in India.

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1. INTRODUCTION

Mining is one of the most significant industrial sectors contributing to economic development and energy security worldwide. In India, the mining industry plays a crucial role in supporting infrastructure growth, electricity generation, and industrial production. Despite its economic importance, mining remains among the most hazardous occupations due to the presence of unstable geological conditions, confined underground environments, high-energy machinery, and exposure to toxic gases and dust. Occupational accidents in mining frequently result in fatalities, injuries, property loss, and environmental degradation, thereby necessitating comprehensive risk management frameworks for sustainable operations (Reason, 1997; Rasmussen, 1997).

Risk in mining can be defined as the probability of occurrence of an undesirable event combined with the severity of its consequences. Mining risks emerge from multiple interacting factors including geological instability, equipment malfunction, operational errors, and inadequate safety management systems (Aven, 2016). Underground mines are particularly vulnerable due to limited ventilation, restricted escape routes, and challenging strata conditions. Previous studies have shown that roof falls, explosions, haulage accidents, and machinery-related incidents remain the dominant causes of mining fatalities worldwide (Kecojevic et al., 2007).

Mining hazards can broadly be categorized into geological, environmental, operational, and human-related hazards. Geological hazards include roof collapses, rock bursts, slope failures, and landslides. Environmental hazards involve methane accumulation, toxic gas emissions, dust pollution, and water inundation. Operational hazards arise during drilling, blasting, transportation, and material handling activities, while human-related hazards originate from fatigue, inadequate training, poor communication, and unsafe behavioral practices (Mohamed, 2002; Hopkins, 2006).

Modern safety management increasingly emphasizes proactive hazard identification and risk mapping techniques rather than reactive accident response mechanisms. Risk mapping enables the visualization and prioritization of hazardous zones, thereby supporting effective decision-making and emergency preparedness (Tubis et al., 2020). Furthermore, advancements in Geographic Information Systems (GIS), Internet of Things (IoT)-based sensors, artificial intelligence (AI), and automation technologies have transformed mining safety management by enabling real-time hazard monitoring and predictive analysis (Sherin et al., 2023).

The primary objectives of this research are to identify critical hazards in Indian mining operations, evaluate different risk assessment methodologies, and develop a comprehensive risk mapping framework using historical accident data and structured risk analysis techniques.

2. LITERATURE REVIEW

Several researchers have emphasized that mining accidents result from a complex interaction between technical failures, environmental uncertainties, and organizational deficiencies. Reason (1997) introduced the concept of organizational accidents and highlighted the role of latent failures in high-risk industries. Rasmussen (1997) further explained that industrial risk management must account for dynamic socio-technical interactions influencing operational safety.

Risk mapping has emerged as an important tool for identifying spatially distributed hazards in mining environments. Tubis et al. (2020) demonstrated that risk visualization significantly improves decision-making efficiency and emergency preparedness in mining operations. Similarly, Sherin et al. (2023) utilized GIS-based techniques to identify high-risk operational zones and optimize safety resource allocation.

Various risk assessment methodologies have been employed in mining industries, including Failure Mode and Effects Analysis (FMEA), Fault Tree Analysis (FTA), Event Tree Analysis (ETA), and probabilistic risk assessment methods. According to Aven (2016), integrating qualitative and quantitative risk assessment approaches improves the reliability of safety management systems. Kecojevic et al. (2007) analyzed equipment-related fatalities in mining operations and concluded that inadequate maintenance practices and operator errors remain major contributors to accidents.

Safety culture is another critical determinant of mining safety performance. Mohamed (2002) observed that organizational commitment and worker participation significantly influence safety behavior and accident prevention. Hopkins (2006) emphasized that safety culture must be integrated into operational planning and management decision-making processes to reduce accident rates effectively.

Recent developments in mining safety research focus on technological innovations such as IoT sensors, artificial intelligence, machine learning, and automation systems. Chen (2025) conducted a multimethod analysis of miners' safety behavior and highlighted the importance of behavioral monitoring systems for accident prevention. Haloui and Li (2025) demonstrated that strong safety culture combined with digital safety technologies substantially improves safety performance in mining industries.

International standards such as ISO 45001 and the International Labour Organization (ILO) Code of Practice provide structured frameworks for occupational health and safety management in mines (ISO, 2018; ILO, 2021). These standards advocate systematic hazard identification, continuous monitoring, worker participation, and continual improvement in safety management systems.

3. METHODOLOGY

3.1 Study Area and Data Collection

The present study focuses on major mining regions in India, particularly Jharkhand, Odisha, and Chhattisgarh, where extensive coal and mineral extraction activities are carried out. These regions were selected because of their high production capacity and comparatively elevated accident rates. Secondary data were collected from annual reports published by the Directorate General of Mines Safety (DGMS), Ministry of Coal statistics, research publications, and safety records from mining operations.

The collected data included accident frequency, fatality rates, hazard categories, operational incidents, and technological interventions implemented between 2016 and 2022. Relevant literature related to mining risk management, GIS-based hazard mapping, and occupational safety was also reviewed for theoretical and analytical support.

3.2 Risk Assessment Framework

A structured multi-level risk assessment framework was adopted in this study incorporating qualitative, semi-quantitative, and quantitative approaches. The qualitative approach involved descriptive classification of hazards into low, moderate, high, and extreme-risk categories based on expert judgment and historical trends. The semi-quantitative approach assigned numerical values to likelihood and consequence parameters using a standardized 1–5 risk scale. Quantitative assessment methods were subsequently used to evaluate probable economic losses and operational impacts associated with hazardous events.

The overall risk level was calculated using the standard risk equation:

$R = L \times C$

where:

- R = Risk Score
- L = Likelihood of occurrence
- C = Consequence severity

The generated risk scores were subsequently categorized into acceptable, moderate, high, and extreme-risk zones for prioritization and control planning.

3.3 Risk Mapping Procedure

Risk mapping was carried out through the identification of hazardous activities including drilling, blasting, transportation, roof support installation, and machinery operation. GIS-based spatial interpretation techniques were conceptually integrated to visualize hazard-prone areas. The methodology further incorporated frequency analysis and severity indexing to prioritize high-risk operational zones.

4. Data Analysis and Results

4.1 Hazard Frequency Distribution

Analysis of historical mining accident data revealed that geological hazards constitute the largest proportion of mining accidents in India. Geological failures such as roof falls and slope instability accounted for approximately 35% of total incidents. Mechanical hazards contributed nearly 25%, while environmental hazards including toxic gas exposure and dust pollution accounted for 20%. Human-related factors such as fatigue, negligence, and inadequate training represented approximately 15% of recorded accidents.

The dominance of geological hazards highlights persistent deficiencies in strata management and underground support systems. Similar findings have been reported by Salguero-Caparrós et al. (2015), who identified ground instability as one of the leading causes of occupational fatalities in mining industries.

4.2 Risk Matrix Analysis

A structured likelihood–consequence matrix was developed to determine risk severity associated with major mining hazards. The results are presented in Table 1.

Table 1. Risk Assessment Matrix for Major Mining Hazards

Hazard Type	Likelihood (L)	Consequence (C)	Risk Score (R)	Risk Level
Roof Fall	5	5	25	Extreme
Machinery Failure	4	4	16	Extreme
Transport Accident	3	3	9	Moderate
Explosion	2	5	10	Moderate
Electrical Hazard	2	3	6	Moderate

The analysis indicates that roof falls represent the highest-risk category with a risk score of 25. Machinery-related hazards also fall within the extreme-risk category due to their high frequency and severe consequences. Transport, explosion, and electrical hazards were categorized as moderate risks requiring continuous monitoring and preventive controls.

4.3 Statistical Trend Analysis

DGMS accident statistics from 2016 to 2022 indicate a gradual reduction in fatal accidents in Indian coal mines. Fatalities decreased from 67 cases in 2016 to 24 cases in 2022, reflecting improvements in safety regulations, enforcement mechanisms, and technological interventions. However, the declining trend is not linear, suggesting that operational variability, environmental uncertainties, and behavioral factors continue to influence accident occurrence.

The analysis further revealed that underground mining operations exhibit significantly higher fatality rates compared to opencast mines due to confined working conditions, ventilation limitations, and strata instability.

5. Safety Measures and Risk Mitigation Strategies

5.1 Engineering Controls

Engineering controls constitute the most effective level of hazard mitigation in mining operations. Advanced roof bolting systems, automated ventilation networks, methane drainage systems, and dust suppression mechanisms have significantly improved underground my safety. Water spraying systems and localized ventilation arrangements effectively reduce respirable dust concentration and minimize occupational health risks associated with pneumoconiosis and silicosis.

Modern mines increasingly employ sensor-based monitoring systems capable of detecting gas accumulation, ground movement, and equipment overheating in real time. These systems enable early warning and rapid emergency response, thereby minimizing accident severity.

5.2 Administrative Controls

Administrative measures such as Standard Operating Procedures (SOPs), safety audits, work permits, emergency preparedness plans, and periodic safety training programs play an important role in reducing operational risks. Worker competency development and continuous safety awareness programs enhance compliance with safe operating procedures and minimize unsafe behavior.

Strong safety culture and management commitment have been identified as critical determinants of safety performance in mining industries (Haloui & Li, 2025). Organizations with proactive safety cultures generally exhibit lower accident rates and improved operational efficiency.

5.3 Personal Protective Equipment (PPE)

Personal Protective Equipment serves as the last line of defense against occupational hazards. Essential PPE in mining operations includes helmets, safety boots, gloves, respirators, ear protection devices, reflective clothing, and self-rescue apparatus. Although PPE cannot eliminate hazards entirely, it significantly reduces injury severity during accident events.

5.4 Technological Interventions

Technological advancements have substantially transformed mining safety management. The implementation of IoT-based monitoring systems demonstrated approximately 45% risk reduction through real-time hazard detection. Automation technologies contributed nearly 40% reduction in operational risks by minimizing direct worker exposure to hazardous zones. Artificial intelligence and machine learning systems improved predictive risk analysis capabilities, leading to approximately 35% reduction in accident probability.

GIS-based spatial risk mapping further supports hazard visualization and safety resource allocation. Integration of AI with GIS and sensor technologies offers significant potential for predictive safety management and intelligent mine monitoring systems.

6. DISCUSSION

The findings of this study confirm that roof falls remain the most critical safety challenge in Indian underground mines. The high frequency of strata-related accidents indicates deficiencies in geological assessment, roof support design, and ground control practices. Similar observations have been reported in previous mining safety studies emphasizing the need for enhanced strata monitoring systems and predictive geotechnical analysis.

The study also demonstrates that technological adoption significantly improves safety performance. However, technological effectiveness depends heavily on organizational commitment, workforce competency, and maintenance efficiency. Many Indian mining operations continue to face implementation barriers due to financial constraints, limited technical expertise, and inadequate safety culture.

Regional analysis indicates that high-production mining zones experience greater risk exposure due to increased operational intensity and equipment utilization. Therefore, site-specific risk mapping and localized safety management strategies are essential for effective hazard control.

The integration of AI, IoT, GIS, and automation technologies represents a transformative approach toward achieving zero-harm mining operations. Nevertheless, technology alone cannot eliminate mining risks entirely. Sustainable safety improvement requires a balanced combination of engineering controls, administrative measures, worker participation, and organizational safety culture.

7. CONCLUSION AND RECOMMENDATIONS

7.1 Conclusion

This study presented a comprehensive framework for risk mapping and safety analysis in the Indian mining industry using structured risk assessment methodologies. The findings indicate that geological hazards, particularly roof falls, constitute the most severe threat to mining safety. Machinery-related incidents also represent significant operational risks requiring immediate attention.

Historical accident analysis demonstrates a gradual decline in mining fatalities due to improved regulatory enforcement and technological advancements. However, underground mining operations continue to exhibit comparatively higher risk levels because of confined environments, ventilation limitations, and complex geological conditions.

The study confirms that risk mapping combined with IoT-based monitoring, AI-driven predictive analytics, and GIS-supported hazard visualization significantly enhances safety management effectiveness. Proactive safety management strategies are therefore essential for sustainable mining operations and accident prevention.

7.2 Recommendations

To improve mining safety performance and minimize accident risks, the following recommendations are proposed:

1. Advanced roof support systems and automated strata monitoring technologies should be widely implemented in underground mines.
2. IoT-based gas detection systems and real-time environmental monitoring should be integrated into mine safety infrastructure.
3. Comprehensive safety training and behavioral safety programs should be strengthened to reduce human error and unsafe work practices.
4. Artificial intelligence and machine learning models should be developed for predictive risk analysis and accident forecasting.
5. GIS-based risk mapping should be incorporated into mine planning and emergency response systems.
6. Mining organizations should adopt international occupational safety standards such as ISO 45001 for continuous safety improvement.

7. Future research should focus on digital mining technologies, autonomous systems, and intelligent safety management frameworks for sustainable mining operations.

REFERENCES

1. Aven T. Risk assessment and management: Review of recent advances. Reliab Eng Syst Saf. 2016.
2. Chen X. Multimethod analysis of miners' safety behaviour. Sci Rep. 2025.
3. Directorate General of Mines Safety (DGMS). Annual report on mine safety in India. Government of India; 2022.
4. Eastman JR. IDRISI GIS and image processing software manual. Clark Labs; 2016.
5. Environmental Systems Research Institute. ArcGIS for mining risk mapping and spatial analysis. ESRI; 2022.
6. Goodchild MF. Citizens as sensors: The world of volunteered geography. GeoJournal. 2007; 69:211-21.
7. Haloui I, Li Y. Safety culture and mining safety performance. Int J Sci Res Arch. 2025.
8. Hollnagel E. Safety-I and Safety-II: The past and future of safety management. Ashgate Publishing; 2014.
9. Hopkins A. Studying organizational cultures and their effects on safety. 2006.
10. International Council on Mining and Metals. Good practice guidance on health and safety risk assessment. 2020.
11. International Labour Organization. Safety and health in mines: Code of practice. Geneva: ILO; 2021.
12. International Organization for Standardization. ISO 45001: Occupational health and safety management systems. Geneva: ISO; 2018.
13. Kecojevic V, Komljenovic D, Groves W, Radomsky M. Equipment-related fatalities in mining. Saf Sci. 2007;45(8):864-74.
14. Ministry of Coal. Coal statistics of India. Government of India; 2022.
15. Mohamed S. Safety climate in construction and mining industries. J Constr Eng Manag. 2002;128(5):375-84.
16. Rasmussen J. Risk management in a dynamic society. Saf Sci. 1997;27(2-3):183-213.
17. Reason J. Managing the risks of organizational accidents. Ashgate Publishing; 1997.
18. Salguero-Caparrós F, Pardo-Ferreira M, Rubio-Romero J. Analysis of occupational accidents in mining. Saf Sci. 2015; 75:148-60.
19. Sherin, et al. GIS-based risk mapping in mining operations. 2023.
20. Tubis, et al. Risk mapping for better decision-making in mining. 2020.

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