Indian Journal of Modern Research and Reviews

This Journal is a member of the *'Committee on Publication Ethics'*

Online ISSN:2584-184X

Research Article

Accident Investigation and Trend Analysis of Indian Coal Mines: A 20-Year Review (2006–2025)

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DOI: https://doi.org/10.5281/zenodo.20266008

Abstract

Coal mining remains one of the most hazardous industrial sectors worldwide, particularly in developing economies such as India, where increasing energy demand continues to drive coal production. This study presents a comprehensive investigation and trend analysis of accidents in Indian coal mines over a twenty-year period from 2006 to 2025. The research utilizes secondary data collected from Directorate General of Mines Safety (DGMS) reports, Ministry of Coal publications, and peer-reviewed scientific literature. The study evaluates trends in fatal accidents, fatalities, serious injuries, accident severity, and causative factors associated with both underground and opencast mining operations.

The findings indicate a substantial decline in fatal accidents and fatalities during the study period, reflecting improvements in mechanization, regulatory enforcement, safety training, and adoption of advanced mining technologies. Fatal accidents declined from 78 cases in 2006 to 21 cases in 2025, while fatalities decreased from 137 to 24 during the same period. Serious injuries and non-fatal accidents also demonstrated considerable reductions. However, despite these improvements, mining accidents continue to pose significant challenges due to persistent hazards such as roof falls, machinery failures, human error, inadequate supervision, gas explosions, and geotechnical instabilities.

The study further reveals a transition in accident patterns from traditional underground hazards toward mechanization-related accidents in opencast mines. While accident frequency has reduced considerably, accident severity remains a concern in recent years. The paper emphasizes the importance of predictive safety management, artificial intelligence-based monitoring systems, Internet of Things (IoT) applications, and stronger organizational safety culture to achieve sustainable my safety. The research provides practical recommendations for policymakers, mining engineers, researchers, and safety professionals for improving occupational health and safety in the Indian coal mining sector.

Manuscript Information

- **ISSN No:** 2584-184X
- **Received:** 04-04-2026
- **Accepted:** 16-05-2026
- **Published:** 18-05-2026
- **MRR:**4(5); 2026: 129-133

- **Plagiarism Checked:** Yes
- **Peer Review Process:** Yes

How to Cite this Article

Meena J P, Gosh G, Suja DIB, Supooh W. Accident investigation and trend analysis of Indian coal mines: A 20-year review (2006–2025). Indian J Mod Res Rev. 2026;4(5):129-133.

Access this Article Online

www.mrrjournal.in

KEYWORDS: Coal mining, accident investigation, DGMS, mine safety, accident trend analysis, occupational hazards, India, risk management, mining accidents, safety culture.

1. INTRODUCTION

Coal mining plays a critical role in the economic and industrial development of India. Coal remains the primary source of energy for thermal power generation and contributes significantly to the steel, cement, and manufacturing industries. The mining sector also provides direct and indirect employment opportunities to millions of workers across the country. Despite its economic importance, coal mining is widely recognized as one of the most hazardous industries because of the complex interaction between geological, technological, environmental, and human factors.

Mining operations involve multiple risks such as roof falls, gas explosions, mine fires, dust exposure, inundation, equipment failure, slope instability, transportation accidents, and electrocution. Underground coal mines are particularly vulnerable to methane explosions, roof collapse, and poor ventilation conditions, whereas opencast mines face increasing risks associated with heavy earth-moving machinery, haulage systems, and slope failures. According to the Directorate General of Mines Safety (DGMS), coal mine accidents continue to result in fatalities, injuries, productivity losses, and environmental damage despite substantial improvements in mining technology and safety regulations (DGMS, 2022).

Accident investigation and trend analysis are essential tools for understanding the root causes of mining accidents and developing effective preventive strategies. Systematic analysis of accident data helps identify high-risk activities, unsafe working conditions, and organizational deficiencies. Over the past two decades, the Indian mining industry has undergone rapid mechanization and modernization. Regulatory reforms, implementation of safety management systems, enhanced training programs, and technological interventions have contributed to improvements in occupational safety performance. However, recurring accidents indicate that several challenges still persist.

Previous studies have emphasized the importance of human behavior, organizational culture, and technological innovation in reducing mining accidents. Human error has been identified as one of the leading causes of accidents in underground mines (Kumar et al., 2020). Similarly, machinery-related accidents in opencast mining have increased with greater dependence on mechanized systems (Duarte et al., 2021). Emerging technologies such as artificial intelligence, IoT-based monitoring systems, and predictive analytics are increasingly being explored for proactive risk management in mining environments (Dey et al., 2021).

In this context, the present study aims to conduct a detailed accident investigation and trend analysis of Indian coal mines during the period 2006–2025. The study evaluates accident patterns, fatality trends, major causes of accidents, and safety improvements achieved over time. The research also proposes recommendations for strengthening mine safety through technological innovation, improved safety culture, and effective risk management strategies.

2. OBJECTIVES OF THE STUDY

The primary objective of this research is to examine accident trends and safety performance in Indian coal mines over a twenty-year period from 2006 to 2025. The study specifically aims to analyze the variation in fatal accidents, fatalities, serious injuries, and accident severity across different mining methods and operational conditions.

Another important objective is to identify the major causes and contributing factors responsible for mining accidents, including human factors, equipment failures, geological conditions, and organizational deficiencies. The study also seeks to compare accident characteristics in underground and opencast coal mines in order to understand the changing nature of mining risks associated with increasing mechanization.

In addition, the research evaluates the effectiveness of safety regulations, technological advancements, and safety management practices implemented in the Indian coal mining sector during the study period. Finally, the study proposes suitable recommendations for improving occupational safety and achieving sustainable mining operations through modern risk management approaches and technological interventions.

3. LITERATURE REVIEW

Mine safety has attracted considerable attention from researchers, regulatory agencies, and mining organizations worldwide. Previous studies have examined accident causation, safety performance, risk assessment techniques, and technological interventions for accident prevention.

Kumar, Gupta, and Gunda (2020) investigated the role of human error in underground coal mine accidents and reported that unsafe behavior, inadequate supervision, and lack of safety awareness significantly contribute to accident occurrence. Their study highlighted the importance of behavioral safety training and human reliability assessment in reducing accidents.

Duarte, Marques, and Baptista (2021) conducted a systematic review of occupational accidents associated with heavy machinery and observed that poor equipment maintenance, improper operation, and inadequate operator training are major causes of machinery-related accidents in mining industries. The researchers emphasized the need for preventive maintenance and operator competency development.

Shahani et al. (2021) applied fuzzy logic techniques for comparative analysis of coal miner fatalities and demonstrated the usefulness of advanced analytical tools in evaluating accident risks and safety performance. Their findings suggested that intelligent risk assessment models can support proactive decision-making in mining operations.

Dey, Chaulya, and Kumar (2021) proposed a hybrid CNN-LSTM and IoT-based hazard monitoring system for coal mines. Their research demonstrated that real-time monitoring of environmental parameters such as methane concentration, temperature, and ground stability can significantly improve accident prevention capabilities.

Sahu and Mishra (2023) examined coal mine explosions in India and concluded that ventilation failures, methane accumulation, and poor safety compliance remain major contributors to explosion-related disasters. Similarly, Wang,

Sui, and Ranville (2022) analyzed groundwater inrush hazards in underground coal mines and emphasized the importance of hydrogeological investigations and real-time monitoring systems.

International studies also provide valuable insights into mining safety management. Kecojevic et al. (2007) analyzed equipment-related fatalities in U.S. mining operations and identified haul trucks, conveyors, and excavation equipment as major sources of fatal accidents. Joy (2004) emphasized the significance of occupational risk management systems in Australian mining industries and advocated for integrated safety management approaches.

Reason (1990) introduced the concept of human error and organizational accidents, explaining how latent organizational failures combine with active failures to produce catastrophic accidents. Mohamed (2002) highlighted the importance of safety climate and organizational commitment in improving workplace safety performance.

The literature indicates that although technological advancements have reduced accident frequency, human factors, organizational deficiencies, and operational risks continue to pose major challenges in mining industries globally. Therefore, comprehensive accident analysis remains essential for continuous safety improvement.

4. METHODOLOGY

4.1 Research Design

The present study adopts a descriptive and exploratory research design using a retrospective approach to analyze accident trends in Indian coal mines over the period 2006–2025. The research focuses on evaluating historical accident data and identifying long-term patterns associated with mining safety performance.

4.2 Data Sources

The study primarily relies on secondary data collected from authentic and reliable sources. Accident statistics and safety records were obtained from Directorate General of Mines Safety (DGMS) annual reports and statistical publications. Additional information was collected from Ministry of Coal reports, research journals, conference proceedings, and international safety publications.

The collected data include information related to fatal accidents, fatalities, serious injuries, accident locations, accident causes, and mining methods. Relevant literature on mining safety, occupational hazards, and risk management was also reviewed to support interpretation and discussion of findings.

4.3 Data Analysis Techniques

The collected data were analyzed using trend analysis and comparative statistical methods. Accident frequencies and fatality rates were examined across different years to identify long-term changes in safety performance. Comparative analysis was conducted between underground and opencast mining operations to evaluate differences in accident patterns and risk characteristics. Accidents were further classified according to their causes, including roof falls, machinery accidents, transportation incidents, explosions, inundation, and human error. Severity analysis was also performed by examining the ratio of injuries per accident. The results were interpreted with reference to technological advancements, regulatory developments, and organizational safety practices implemented during the study period.

5. RESULTS AND ANALYSIS

5.1 Trend of Fatal Accidents

The analysis of DGMS accident records indicates a substantial reduction in fatal accidents in Indian coal mines over the last two decades. In 2006, approximately 78 fatal accidents were recorded in coal mining operations, whereas only 21 fatal accidents were reported in 2025. This represents an overall reduction of nearly 73% in fatal accident frequency.

The decreasing trend reflects improvements in mine planning, mechanization, safety awareness, and regulatory enforcement. The introduction of advanced monitoring systems, better communication technologies, and stricter compliance with safety standards has contributed significantly to reducing accident occurrence. Increased use of mechanized mining methods has also reduced direct worker exposure to hazardous underground conditions.

However, occasional spikes in accident occurrence were observed during certain years due to major disasters, machinery failures, and operational negligence. The findings indicate that although accident frequency has reduced considerably, coal mining remains inherently hazardous.

5.2 Trend of Fatalities

Fatality trends also demonstrate significant improvement during the study period. Fatalities declined from approximately 137 deaths in 2006 to 24 deaths in 2025. The reduction in fatalities can be attributed to improved emergency preparedness, rescue systems, training programs, and implementation of safety management systems.

The decline in fatalities also reflects better enforcement of statutory provisions under DGMS regulations and increased awareness among mine workers regarding occupational hazards. Technological innovations such as gas monitoring systems, slope stability analysis, and remote-controlled equipment have further improved worker safety.

Despite the decline, certain catastrophic accidents involving explosions, roof falls, and machinery incidents continue to result in multiple fatalities. This indicates that while routine safety management has improved, high-risk scenarios still require enhanced preventive measures.

5.3 Serious Accidents and Injuries

The study observed a remarkable decline in serious accidents and injuries in Indian coal mines. Serious accidents decreased from approximately 861 cases in 2006 to 49 cases in 2025, while serious injuries reduced from 876 to 57 during the same period.

This improvement reflects better hazard identification, safer work procedures, improved personal protective equipment (PPE), and enhanced safety supervision. Safety awareness

campaigns and worker training programs implemented by mining companies and regulatory agencies have also contributed to reducing non-fatal injuries.

Mechanization has minimized manual handling activities and reduced worker exposure to dangerous environments. However, increased dependence on heavy machinery has introduced new challenges associated with operator safety, equipment maintenance, and transportation hazards.

5.4 Injury per Accident Analysis

The average injury-per-accident ratio during the study period was approximately 1.05, indicating that most accidents continued to result in at least one serious injury. Recent years showed relatively higher severity values approaching 1.4, suggesting that while accident frequency has reduced, the severity of individual accidents has increased.

This trend may be associated with the increasing scale of mechanized mining operations where machinery-related accidents often result in severe injuries or multiple casualties. The findings emphasize the importance of focusing not only on accident frequency reduction but also on minimizing accident severity through better engineering controls and emergency response systems.

5.5 Place-wise Distribution of Accidents

Analysis of accident location data revealed that opencast mines accounted for approximately 47.65% of total accidents, while underground mines contributed around 44.11%. Aboveground facilities accounted for the remaining 8.24% of accidents.

Although opencast mines reported a higher number of accidents due to large-scale mechanized operations, underground mines exhibited greater accident severity because of confined working conditions, poor visibility, methane accumulation, and roof instability. Roof falls, gas explosions, and inundation remained dominant hazards in underground mining operations.

The increasing share of accidents in opencast mines reflects rapid mechanization and expansion of surface mining activities in India. Transportation systems, dumpers, excavators, and conveyor systems emerged as major contributors to accidents in surface mines.

6. DISCUSSION

6.1 Major Causes of Mining Accidents

The analysis identified multiple interrelated factors contributing to mining accidents in Indian coal mines. Human factors such as inadequate training, negligence, fatigue, unsafe work practices, and poor compliance with safety procedures remain dominant contributors to accidents. Human error has been widely recognized as a critical factor in mining incidents because mining operations often involve complex decision-making under hazardous conditions (Reason, 1990).

Technical factors also play an important role in accident occurrence. Equipment failure, poor maintenance, outdated machinery, and electrical faults contribute significantly to machinery-related accidents. Increasing mechanization in opencast mines has introduced new operational risks associated with heavy earth-moving machinery and haulage systems.

Geological factors such as roof falls, methane explosions, water inrush, and slope instability continue to threaten underground mining operations. Poor geological assessment and inadequate ground control practices can result in catastrophic accidents with multiple fatalities.

Organizational deficiencies including weak safety culture, inadequate supervision, production pressure, and ineffective communication further aggravate accident risks. Studies have shown that organizations with strong safety culture and leadership commitment generally achieve better safety performance (Mohamed, 2002).

6.2 Shift in Accident Patterns

The study revealed a gradual shift in accident patterns over the last two decades. Earlier mining accidents were predominantly associated with underground hazards such as roof falls, explosions, and ventilation failures. However, with increasing mechanization and expansion of opencast mining, machinery-related accidents have become more prominent.

The transition toward mechanized mining has reduced certain traditional hazards but introduced new risks involving dumpers, excavators, drilling equipment, and transportation systems. Therefore, modern mining safety strategies must address both conventional underground hazards and emerging mechanization-related risks.

6.3 Safety Improvements in Indian Coal Mines

Significant safety improvements have been observed in the Indian coal mining industry during the study period. Mechanization and automation have reduced worker exposure to hazardous conditions and improved operational efficiency. The implementation of DGMS regulations and regular safety inspections has strengthened compliance with statutory safety standards.

Mining companies have increasingly adopted safety management systems, risk assessment procedures, and worker training programs. Real-time monitoring technologies, gas detection systems, and communication networks have further enhanced safety preparedness.

Despite these improvements, accident recurrence indicates that continuous safety improvement efforts are still necessary. Sustainable safety performance requires integration of technological innovation, behavioral safety, organizational commitment, and proactive risk management.

7. Recommendations

Advanced technological interventions should be adopted to further improve mine safety in India. Artificial intelligence-based predictive safety systems can help identify hazardous conditions before accidents occur. IoT-enabled sensors can provide real-time monitoring of methane concentration, temperature, ventilation conditions, equipment performance, and ground stability. Automation and remote-controlled machinery should be expanded in hazardous mining areas to minimize worker exposure.

Regulatory enforcement should be strengthened through regular safety audits, inspections, and strict compliance monitoring.

DGMS regulations must be updated periodically to address emerging risks associated with modern mechanized mining systems. Mining organizations should establish robust accountability mechanisms to ensure implementation of safety standards at all operational levels. Human factors must receive greater attention through continuous safety education, skill development programs, and behavioral safety training. Fatigue management systems, shift scheduling improvements, and psychological safety programs can help reduce human error and unsafe behavior. Risk-based safety management approaches such as Safety Management Plans (SMP) and Trigger Action Response Plans (TARP) should be implemented comprehensively across mining operations. Systematic hazard identification and risk assessment must become integral components of operational planning. Emergency preparedness should also be enhanced through advanced mine rescue systems, mock drills, disaster management planning, and rapid response mechanisms. Integration of digital communication technologies can improve coordination during emergency situations.

8. CONCLUSION

The present study analyzed accident trends and safety performance in Indian coal mines over the period 2006–2025. The findings demonstrate that substantial improvements have been achieved in reducing fatal accidents, fatalities, and serious injuries during the last two decades. Mechanization, improved safety regulations, enhanced training programs, and technological advancements have collectively contributed to safer mining operations.

However, mining continues to remain a high-risk industry due to persistent challenges associated with human error, machinery hazards, geological uncertainties, and organizational deficiencies. Although accident frequency has reduced significantly, accident severity remains a critical concern in recent years. The study emphasizes that future mine safety strategies should focus on predictive risk management, artificial intelligence-based monitoring systems, organizational safety culture, and proactive hazard control measures. Achieving sustainable and zero-harm mining operations requires continuous innovation, strict regulatory compliance, effective leadership commitment, and active worker participation in safety management. The research findings provide valuable insights for policymakers, mining engineers, safety professionals, and researchers working toward improving occupational health and safety in the Indian coal mining industry.

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