Indian Journal of Modern Research and Reviews

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

Online ISSN:2584-184X

Research Article

Evaluation of Safety Management Systems in Coal Mining Operations in India

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DOI: https://doi.org/10.5281/zenodo.20255143

Abstract

Coal mining constitutes a major component of India's industrial and energy infrastructure, contributing substantially to electricity generation and economic development. Despite technological advancement, mining operations continue to remain highly hazardous because of geological uncertainties, operational complexities, and unsafe working conditions. The present study evaluates the effectiveness of Safety Management Systems (SMS) implemented in Indian coal mining operations through analysis of hazard identification procedures, risk assessment techniques, accident frequency, and severity indices. The study emphasizes the importance of systematic safety planning, proactive hazard control, worker training, and regulatory compliance under the Directorate General of Mines Safety (DGMS). Comparative evaluation of four coal mines was conducted using safety performance indicators including Accident Frequency Rate (AFR) and Severity Rate (SR). Results indicate significant variation in safety performance among mines, primarily due to differences in implementation efficiency, worker awareness, emergency preparedness, and management commitment. Mine D demonstrated superior safety performance with the lowest AFR and SR values, while Mine C exhibited poor safety outcomes due to inadequate hazard mitigation measures. The research concludes that integration of advanced technologies such as IoT-based monitoring systems, real-time gas detection, and simulation-based training can substantially improve mine safety performance. The study provides practical recommendations for strengthening safety culture and establishing sustainable accident prevention strategies in Indian coal mines.

Manuscript Information

- **ISSN No:** 2584-184X
- **Received:** 19-04-2026
- **Accepted:** 14-05-2026
- **Published:** 17-05-2026
- **MRR:**4(5); 2026: 106-109

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

How to Cite this Article

Ravi S K, Mehta P R, Kumar G, Chaudhary A, Kumar C, Pradhan A K. Evaluation of safety management systems in coal mining operations in India. Indian J Mod Res Rev. 2026;4(5): 106-109.

Access this Article Online

www.mrrjournal.in

KEYWORDS: Coal Mining, Safety Management System, Risk Assessment, DGMS, Accident Frequency Rate, Mine Safety.

1. INTRODUCTION

1.1 Background

India is among the largest coal-producing countries in the world, with extensive reserves concentrated in states such as Jharkhand, Odisha, Chhattisgarh, and West Bengal. Coal remains the dominant source of energy for thermal power generation and industrial production in India. Both opencast and underground mining methods are extensively practiced to meet increasing energy demands. However, mining operations are associated with numerous occupational hazards including roof falls, slope failures, explosions, fires, dust exposure, and machinery-related accidents. These hazards not only threaten workers' lives but also result in substantial economic losses and environmental degradation. Therefore, implementation of an effective Safety Management System (SMS) has become an essential requirement for sustainable mining operations (Singh, 2015; Tripathy & Ala, 2018).

The Directorate General of Mines Safety (DGMS) acts as the principal regulatory authority responsible for enforcement of mine safety legislation in India. The Mines Act, 1952 and Coal Mines Regulations, 2017 provide the legal framework governing occupational safety, health, and welfare in mining operations (Padhi, 1998). Although significant improvements have been achieved over recent decades, accident statistics still indicate recurring safety lapses in many Indian coal mines.

1.2 Importance of Safety Management in Coal Mines

Mining environments are inherently hazardous due to complex geological formations and the continuous interaction between humans, machinery, and explosives. In underground coal mines, roof collapse, methane gas explosions, and spontaneous heating constitute major risks. In opencast mines, slope instability, blasting hazards, haul road accidents, and heavy equipment failures are common causes of injuries and fatalities. Effective safety management is therefore essential for reducing accident rates, improving worker productivity, minimizing operational disruptions, and ensuring regulatory compliance (Maiti & Bhattacherjee, 2000).

Modern safety management emphasizes a preventive rather than reactive approach. Instead of responding only after accidents occur, organizations are increasingly focusing on hazard identification, risk assessment, continuous monitoring, and behavioral safety improvement. Development of a strong safety culture within mining organizations is considered one of the most effective measures for long-term accident prevention (Verma & Chaudhari, 2017).

1.3 OBJECTIVES OF THE STUDY

The major objectives of the present research are:

1. To evaluate the effectiveness of Safety Management Systems in Indian coal mines.
2. To analyze accident frequency and severity indicators for selected mines.
3. To identify critical gaps in current safety practices and implementation strategies.
4. To recommend advanced technological and managerial approaches for improving mine safety performance.

2. LITERATURE REVIEW

Safety management in mining has attracted considerable global attention due to the hazardous nature of mining operations. Advanced mining nations such as Australia and the United States have significantly reduced accident rates through automation, digital monitoring systems, and systematic risk management practices (Esterhuizen & Gürtunca, 2006). Studies indicate that real-time environmental monitoring and predictive analytics can substantially improve hazard detection and emergency response capabilities.

In India, safety management practices are primarily governed by DGMS regulations. Tripathy and Ala (2018) identified major hazards in underground coal mines and emphasized the importance of structured hazard identification systems. Verma and Chaudhari (2017) analyzed worker safety in Indian mines and concluded that unsafe acts, inadequate supervision, and lack of safety awareness are major contributors to mining accidents.

Maiti and Bhattacherjee (2000) developed a causal model for evaluation of mine safety and demonstrated that organizational and behavioral factors significantly influence accident occurrence. Similarly, Singh and Singh (2023) examined coal mine explosions in India and reported that management failures and safety lapses were major causes of catastrophic incidents.

Recent research has increasingly focused on technology-driven safety systems. Mercy Rajaselvi *et al.* (2020) discussed coal mine safety monitoring systems based on sensor networks and wireless communication technologies. Appiah *et al.* (2023) conducted a bibliometric analysis of global safety trends in coal mining and highlighted the growing importance of automation, artificial intelligence, and smart monitoring systems in improving occupational safety.

The Plan-Do-Check-Act (PDCA) cycle forms the theoretical basis of most Safety Management Systems. Under this framework, hazards are identified during the planning stage, safety measures are implemented during execution, performance is continuously monitored, and corrective actions are introduced to eliminate deficiencies. Such a systematic approach promotes continuous safety improvement and proactive accident prevention.

3. METHODOLOGY

3.1 Risk Assessment Procedure

The present study adopted a quantitative risk assessment approach to evaluate mine safety performance. Hazards associated with mining operations were identified through analysis of accident records, safety reports, field observations, and previous literature. Risk was estimated using the standard formula:

Risk = Probability X Severity

Where probability represents the likelihood of occurrence of a hazardous event and consequence represents the severity of its impact.

The risk assessment process involved hazard identification, evaluation of exposure conditions, determination of likelihood, estimation of consequences, and prioritization of control measures. This approach enabled systematic classification of hazards according to their risk levels.

3.2 Slope Stability Analysis

For opencast coal mines, slope stability is one of the most important safety concerns. The stability condition of mine slopes was evaluated using the Factor of Safety (FOS):

$$\mathbf{FOS} = \frac{\text{Shear Strength}}{\text{Shear Stress}}$$

A stable slope generally requires an FOS value greater than 1.3 under normal operating conditions. The shear strength of rock masses was estimated using the Mohr–Coulomb failure criterion:

$$T = c + \sigma \tan \phi$$

Where:

- τ = Shear strength
- c = Cohesion
- σ = Normal stress
- ϕ = Angle of internal friction

The analysis provided insight into the influence of geotechnical parameters on slope stability and my safety.

3.3 Safety Performance Indicators

The effectiveness of the Safety Management System was evaluated using two major safety indices:

Accident Frequency Rate (AFR)

$$\mathbf{AFR} = \frac{\text{Number of Accidents} \times 10^6}{\text{Total Man} - \text{hours Worked}}$$

Severity Rate (SR)

$$\mathbf{SR} = \frac{\text{Number of Lost Days} \times 10^6}{\text{Total Man} - \text{hours Worked}}$$

These indicators are widely used in mining industries for measuring accident occurrence and severity.

4. DATA ANALYSIS AND RESULTS

4.1 Comparative Safety Evaluation

A comparative study was conducted on four coal mines designated as Mine A, Mine B, Mine C, and Mine D. Safety performance data including accident frequency, lost workdays, and man-hours worked were analyzed to evaluate the effectiveness of their respective Safety Management Systems.

Table 1: Comparative Safety Data of Selected Mines

Mine	Number of Accidents	Lost Days	Man-hours Worked	AFR	SR
Mine A	12	240	500,000	24.00	480.00
Mine B	8	160	400,000	20.00	400.00
Mine C	15	450	600,000	25.00	750.00
Mine D	5	100	300,000	16.67	333.33

The analysis revealed significant differences in safety performance among the mines. Mine D demonstrated the best performance with the lowest AFR and SR values, indicating effective hazard control measures, better worker awareness, and stronger emergency preparedness systems. In contrast, Mine C exhibited the highest accident frequency and severity rates, reflecting deficiencies in safety implementation, supervision, and risk mitigation practices.

The results further indicate that severity rates varied more significantly than accident frequency rates. This suggests that although accident occurrence may be similar across mines, the consequences of accidents largely depend on emergency response efficiency, medical support systems, and preparedness measures.

4.2 DISCUSSION

The findings confirm that the implementation quality of Safety Management Systems strongly influences accident prevention and injury reduction. Mines with better training programs, regular inspections, effective communication systems, and technological integration achieved superior safety outcomes. Conversely, mines with inadequate supervision, poor compliance, and insufficient worker participation experienced higher accident severity.

Human factors were also observed to play a crucial role in accident occurrence. Worker fatigue, negligence, lack of skill development, and non-compliance with safety procedures contributed significantly to unsafe conditions. These observations are consistent with previous studies conducted by Verma and Chaudhari (2017) and Maiti and Bhattacherjee (2000).

The study additionally highlights the growing role of digital technologies in mining safety management. IoT-enabled gas sensors, wearable monitoring devices, automated warning systems, and artificial intelligence-based predictive models can substantially improve real-time hazard detection and risk management.

5. CONCLUSION

The present study evaluated the effectiveness of Safety Management Systems in Indian coal mining operations through analysis of safety indicators, risk assessment procedures, and comparative mine performance. The results clearly demonstrate that structured and effectively implemented SMS frameworks significantly reduce accident frequency and severity. Mines with proactive safety policies, continuous monitoring systems, and strong safety culture exhibited better operational performance and lower injury rates.

Despite the existence of comprehensive safety legislation under DGMS guidelines, inconsistencies in implementation remain a major challenge in Indian coal mines. Mine C particularly highlighted how inadequate hazard management and weak enforcement can result in severe safety consequences. The study therefore emphasizes the need for continuous improvement, technological integration, and behavioral safety enhancement in mining operations.

5.2 RECOMMENDATIONS

Mine C requires immediate intervention through detailed safety audits and root-cause analysis to identify critical weaknesses in its safety management practices. Mining organizations should adopt advanced technologies such as IoT-based smart helmets, wireless environmental monitoring systems, and real-time gas detection sensors for early hazard warning and emergency response.

Simulation-based training using virtual reality (VR) technology should be standardised across mining operations to improve worker preparedness during emergencies. Safety awareness programs and behavioural training initiatives should also be strengthened to enhance worker participation and accountability.

In addition, successful safety practices adopted by high-performing mines such as Mine D should be replicated across other mining operations. Establishment of a strong safety culture supported by management commitment, worker involvement, and continuous monitoring is essential for sustainable accident prevention and long-term operational excellence.

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