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Effectiveness Evaluation of Risk-Based SMKP Minerba Audit in Loading-Hauling-Dumping Activities for High Potential Incident Control in Open-Pit Coal Mining

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Abstract

This study evaluates the effectiveness of risk-based audit implementation of the Mineral and Coal Mining Safety Management System (SMKP Minerba) in loading-hauling-dumping activities for controlling High Potential Incidents (HPI) in open-pit coal mines. Loading-hauling-dumping is a core production sequence with high exposure to mobile equipment interaction, haul-road conditions, dumping-point stability, operator fatigue, blind spots, braking failure, and communication breakdown. The study adopts a mixed-methods approach with an evaluative case study design. Quantitative analysis is used to assess audit scores, HPI frequency, corrective action close-out, critical control verification, and the audit effectiveness index. Qualitative analysis is used to examine implementation gaps, control quality, supervisory practices, and barriers to completing audit findings. Data sources include SMKP audit documents, HPI and near-miss reports, corrective action registers, haul-road inspection records, pre-start inspection reports, fatigue or fit-to-work records, field observations, and semi-structured interviews with operational and safety personnel. The proposed evaluation framework integrates audit compliance score, critical control verification score, corrective action realization, and HPI reduction performance. Academic simulation results indicate that risk-based SMKP auditing can improve audit performance, strengthen critical control verification, reduce repeated findings, and decrease HPI rate. However, the close-out of major findings and overdue corrective actions remain important improvement areas. The study contributes an operational audit framework that shifts SMKP evaluation from administrative compliance toward risk-based assurance, emphasizing the prevention of fatal and serious incident potential in open-pit coal mining operations.

Keywords*: SMKP Minerba, Risk-Based Audit, Loading-Hauling-Dumping, High Potential Incident, Critical Control*

1. Introduction

Loading-hauling-dumping activities are the core of open-pit coal mining operations. This sequence involves intensive interactions among excavators, dump trucks, dozers, graders, water trucks, light vehicles, haul roads, loading points, disposal areas, stockpiles, and mine traffic control. The complexity of heavy-equipment interaction and the high exposure of workers to mechanical energy create a significant potential for High Potential Incidents (HPI) [12], [2].

In Indonesia, mining safety risk control cannot be separated from the implementation of the Mineral and Coal Mining Safety Management System, or SMKP Minerba. SMKP Minerba functions as a management system that integrates policy, planning, implementation, monitoring, evaluation, and improvement of mining safety performance [21], [19], [20]. Previous studies indicate that SMKP implementation contributes to improved safety performance, although its effectiveness is strongly influenced by implementation quality, audit quality, and corrective follow-up [18], [16].

SMKP Minerba should not be understood merely as an administrative system, but as an instrument for operational risk control. SMKP audits play an important role in measuring the achievement level of system implementation through both internal and external audits [3], [8]. In practice, however, SMKP audits are often treated as a document-compliance process. An audit may produce a high conformity score, but this does not necessarily confirm whether the audit is effective in controlling potentially fatal events [9], [5].

In loading-hauling-dumping activities, common HPI scenarios include dump-truck collision with light vehicles, loss of control on descending roads, dump-truck rollover on ramps or disposal areas, units entering excavator blind spots, bundwall failure at dumping areas, operator microsleep, and communication failure between operators and supervisors. Powered haulage and haul-truck safety are important issues in mining safety because they are directly associated with the potential for serious injury and fatality [12], [11], [4].

The critical control management approach is relevant because HPI generally occurs not only due to the presence of hazards, but also due to failure of critical controls. Critical control management emphasizes the identification of critical controls, assignment of accountability, verification of control effectiveness, and continuous evaluation of material-risk controls [7], [6]. Therefore, this study evaluates the effectiveness of risk-based SMKP Minerba audit implementation in loading-hauling-dumping activities, particularly in controlling HPI in open-pit coal mining.

From a literature perspective, SMKP Minerba is a management system used to ensure that mining safety is managed systematically, documented, measured, and continuously improved [21], [19], [17]. Risk management within SMKP includes hazard identification, risk assessment, risk control, and monitoring and review. In mining, the risk management process must be able to identify dynamic operational hazards, particularly in activities involving heavy-equipment interaction and high-energy exposure [5], [15].

SMKP audits serve as instruments for measuring performance and the achievement of SMKP implementation. Internal and external audits are used to assess the extent to which SMKP elements have been implemented, but audit effectiveness depends heavily on the audit's ability to identify gaps between documented systems and field practice [3], [8]. Risk-based auditing prioritizes high-risk areas, activities, or processes; therefore, an audit should not merely verify the existence of procedures, but should also test the effectiveness of controls in activities with fatality potential [9], [1].

A High Potential Incident is an event with the potential to cause fatality or serious injury even when the actual consequence is not fatal. In loading-hauling-dumping activities, HPI may include unit collision, dump-truck rollover, loss of control, excavator blind spots, bundwall failure, operator fatigue, and communication failure [12], [14]. Loading-hauling-dumping is the center of open-pit production operations; therefore, haulage-system safety, road conditions, and heavy-equipment interaction management are important aspects [2], [4].

The gap between compliance audits and effective risk control is an important basis for this study. SMKP audits may show good compliance scores, but these scores do not necessarily reflect actual field risk-control effectiveness when they are not supported by critical control verification and follow-up evaluation of audit findings [3], [9]. The effectiveness of risk-based SMKP audits can be assessed through a combination of audit compliance indicators, critical control verification, corrective action completion, HPI reduction, reduction of repeated findings, and improvement of safety leading indicators [9], [6], [10].

2. Research Methods

This study uses a mixed-methods approach with an evaluative case study design. The quantitative approach is used to assess audit scores, HPI frequency, corrective action close-out, and the control effectiveness index, whereas the qualitative approach is used to understand the causes of audit ineffectiveness, the quality of control implementation, and barriers to completing audit findings. This combined approach is relevant for mining safety studies because it links numerical safety data with the operational implementation context in the field [5], [9].

The constructive research steps begin with determining the research design, separating quantitative and qualitative approaches, integrating data and information, defining the scope of risk-based auditing, identifying HPI scenarios, preparing a risk-based audit checklist, assessing risk-based audit scores, calculating the audit effectiveness index, analyzing results, and preparing conclusions and recommendations.

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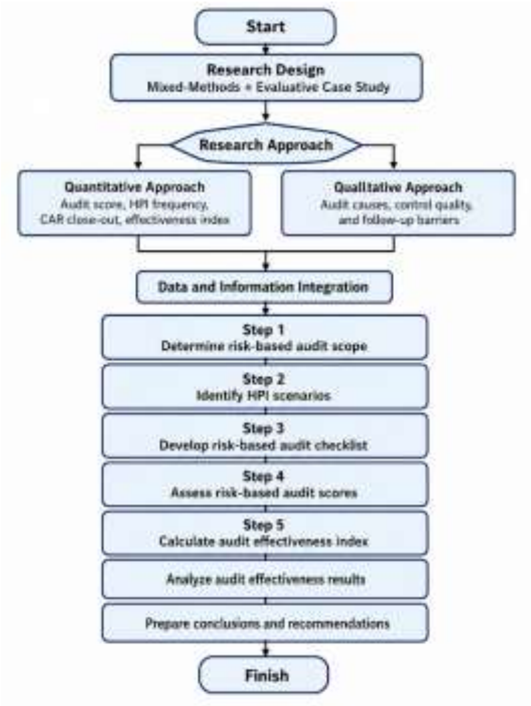

Figure 1. Flowchart of the proposed constructive research steps

Table 1. HPI Scenario Identification

Code	HPI Scenario	Activity	Potential Consequence
HPI-01	Collision between dump truck and light vehicle	Hauling	Fatality
HPI-02	Dump truck loss of control	Hauling	Fatality/major injury
HPI-03	Unit rollover at disposal area	Dumping	Fatality
HPI-04	Unit entering excavator blind spot	Loading	Fatality
HPI-05	Bundwall failure	Dumping	Fatality
HPI-06	Operator microsleep	Hauling	Fatality
HPI-07	Brake failure on descending road	Hauling	Fatality
HPI-08	Positive communication failure	Loading/Hauling	Major injury/fatality

Table 2. Development of the Risk-Based Audit Checklist

Audit Element	Examination Indicator	Audit Evidence
Hazard identification	LHD hazards have been identified	IBPR/JSA/HIRADC
Risk assessment	HPI risks have been rated	Risk register
Risk control	Critical controls have been defined	Critical control list
Control implementation	Controls are implemented at the front, haul road, and disposal	Field observation

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Monitoring	Inspections and verifications are conducted periodically	Inspection record
Follow-up	Findings are closed on time	Corrective action register
Effectiveness evaluation	HPI trends decrease or controls improve	HPI dashboard

Table 3. Audit Scoring Scale

Score	Criteria
0	No evidence of implementation
1	Document exists, but implementation is very limited
2	Partial implementation, not yet consistent
3	Adequate implementation, but effectiveness evaluation is not yet strong
4	Effective implementation, verified and continuously improved

The audit effectiveness index is calculated by combining the audit compliance score, critical control verification score, corrective action realization, and HPI reduction performance. The proposed formula is as follows.

$$IEA = (0.30 \times ACS) + (0.30 \times CCV) + (0.20 \times CAR) + (0.20 \times HPI) \quad (1)$$

IEA is the Audit Effectiveness Index, ACS is the Audit Compliance Score, CCV is the Critical Control Verification Score, CAR is Corrective Action Realization, and HPI is HPI Reduction Performance.

Table 4. Audit Effectiveness Index Interpretation

IEA Value	Category
0-59	Ineffective
60-74	Moderately effective
75-84	Effective
85-100	Highly effective

2.1. Theory Development and Solution Implementation

This study develops the theoretical argument that the effectiveness of SMKP Minerba auditing is not sufficient when measured only by compliance with system elements, document completeness, or fulfillment of administrative procedures. Audit effectiveness should be assessed by the audit's ability to strengthen critical controls and control High Potential Incidents in loading-hauling-dumping activities. In implementation terms, this study proposes the Risk-Based SMKP Audit Framework for LHD Activities as an audit framework that is more operational and relevant to open-pit coal mining activities.

The framework consists of five main components: HPI scenario mapping to map major HPI scenarios in loading, hauling, and dumping activities; critical control mapping to identify and define critical controls for each HPI scenario; field verification to verify the effectiveness of control implementation in the field; corrective action governance to assess the quality, timeliness, and completion of audit finding follow-up; and effectiveness review to evaluate whether the audit produces measurable improvements in both leading and lagging indicators.

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3. Results and Discussions

3.1. Actual Data and Testing Data

The actual data note in this study explains that the results section should be filled with field data obtained directly from the mining company or site. The minimum required data include at least two periods of internal SMKP audit reports, lists of audit findings related to loading-hauling-dumping, corrective action registers, HPI or near-miss reports, haul-road inspection reports, heavy-equipment pre-start inspection reports, fatigue or fit-to-work reports, data on haul cycles, working hours, number of units, exposure hours, field observation results, and interviews with the Head of Mine Engineering, operational supervisors, internal auditors, dump truck operators, dispatchers, and the HSE team. Because actual site data are not yet available, the values in this study use academic simulation data based on audit scenarios and research charts.

Table 5. Data on Risk-Based SMKP Audit Implementation

Audit Element	Risk Weight	Before Audit	After Audit	Change	Data Source
LHD hazard identification	10%	62%	84%	+22 points	IBPR/HIRADC
HPI risk assessment	10%	58%	82%	+24 points	Risk register
Traffic management control	15%	64%	88%	+24 points	SOP/TMP/observation
Haul-road control	15%	60%	86%	+26 points	Road inspection
Dumping-point control	10%	66%	87%	+21 points	Disposal inspection
Fatigue management	10%	55%	81%	+26 points	Fit-to-work/fatigue report
Pre-start inspection and unit roadworthiness	10%	68%	89%	+21 points	P2H/maintenance record
Positive communication	10%	61%	85%	+24 points	Observation/radio log
Audit finding follow-up	10%	57%	83%	+26 points	CAR register

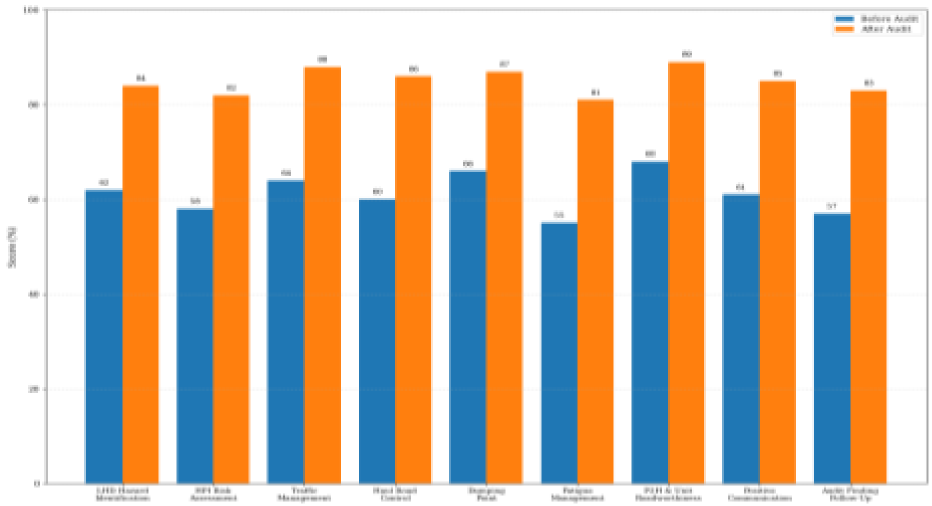

Figure 2. Comparison of risk-based SMKP audit implementation scores before and after audit

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Table 6. Data High Potential Incident

Period	Loading HPI	Hauling HPI	Dumping HPI	Total HPI	Exposure Hours	HPI Rate
Before audit	6	14	8	28	1,200,000	23.33
After audit	3	8	4	15	1,200,000	12.50

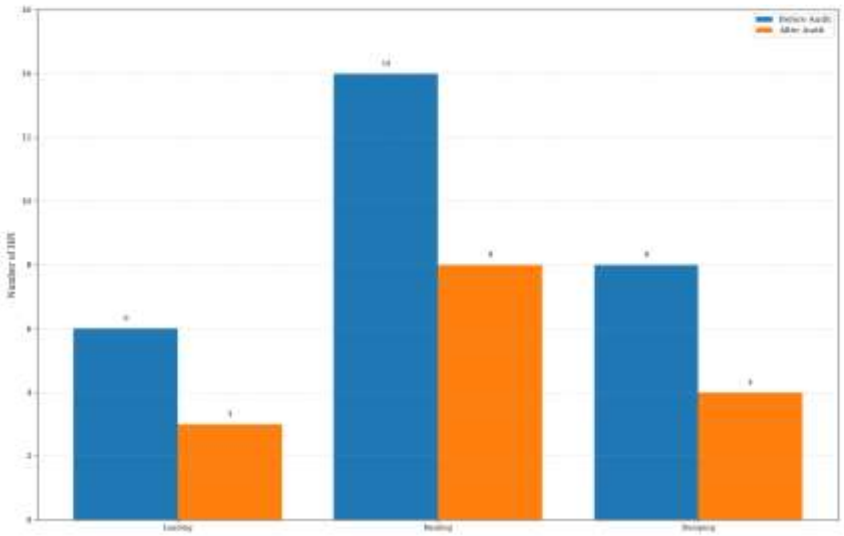

Figure 3. Comparison of High Potential Incident numbers in loading-hauling-dumping activities before and after audit

HPI Rate = (Number of HPI / Exposure Hours) x 1,000,000 (2)

Table 7. Data Corrective Action

Finding Category	Total Findings	Closed	Open	Overdue	Close-Out Rate
Major	11	8	2	1	72.73%
Minor	21	15	4	2	71.43%
Observation	16	12	3	1	75.00%
Critical Control Gap	10	7	2	1	70.00%

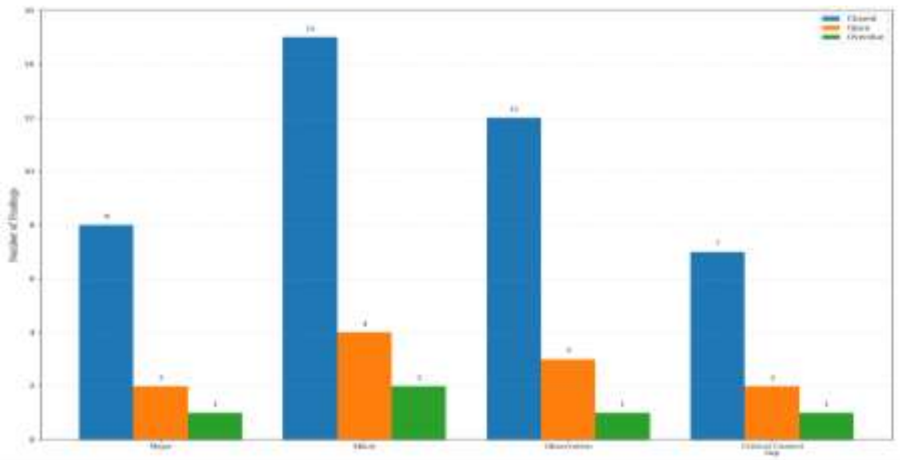

Figure 4. Follow-up status of risk-based SMKP audit findings

Close-Out Rate = (Number of Closed Findings / Total Findings) x 100% (3)

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3.2. Testing Instruments and Testing Implementation

The testing instruments include a risk-based SMKP audit checklist, HPI risk matrix, critical control verification sheet, corrective action register review form, field observation sheet, and semi-structured interview guide. The checklist is developed based on SMKP elements, risk management, loading-hauling-dumping SOPs, traffic management plans, haul-road standards, fatigue management, and critical control verification.

Testing is implemented through desk review, field audit, critical control verification, and effectiveness evaluation. The desk review covers SMKP audit documents, IBPR, JSA, loading-hauling-dumping SOPs, traffic management plans, haul-road inspection reports, fatigue reports, pre-start inspection reports, and the HPI register. The field audit is conducted at loading points, main haul roads, intersections, ramps, disposal areas, stockpiles or ROM areas, unit parking areas, dispatch rooms, workshops, and supervisor posts.

Table 8. Verified Critical Controls

HPI Scenario	Critical Controls
Collision between dump truck and light vehicle	traffic segregation, positive communication, speed control
Loss of control	road gradient control, berm/windrow, brake test
Rollover at disposal area	dumping procedure, bundwall, spotter, lighting
Excavator blind spot	exclusion zone, radio communication, spotter
Microsleep	fatigue monitoring, fit-to-work, roster control
Brake failure	P2H, maintenance, brake test ramp
Slippery/dusty road	road maintenance, watering, road inspection

Table 9. Testing Evaluation

Indicator	Before Audit	After Audit	Target	Status
Risk-based audit score	61.30%	85.20%	>=85%	Achieved
Critical control verification score	63%	91%	>=90%	Achieved
Close-out rate of major findings	50.00%	72.73%	100%	Not achieved
HPI rate	23.33	12.50	decrease >=20%	Achieved
Overdue corrective actions	9 findings	5 findings	0	Not achieved
Repeated findings	20 findings	9 findings	decrease >=50%	Achieved
Fatigue-related HPI	6 HPI	4 HPI	decrease	Achieved
Road-condition-related HPI	7 HPI	5 HPI	decrease	Achieved

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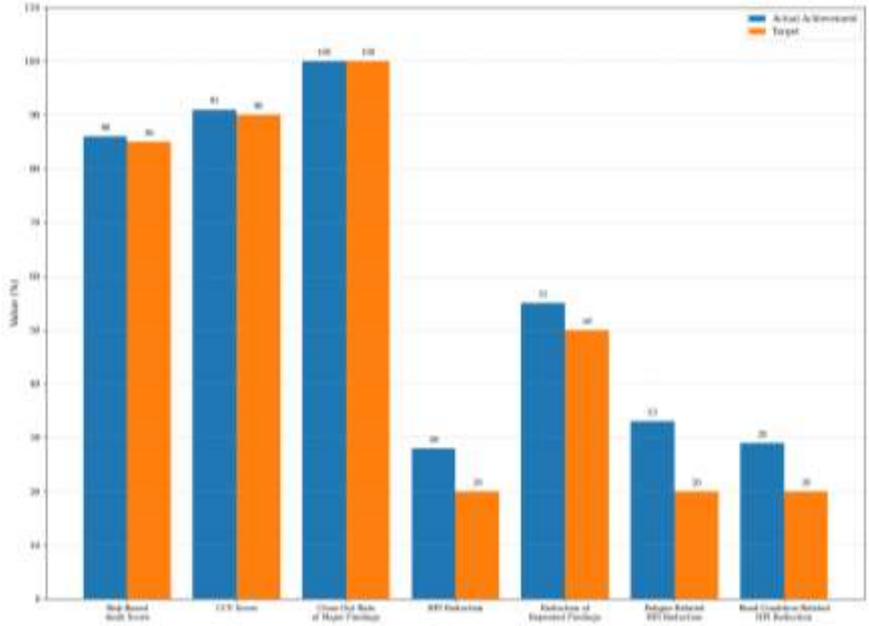

Figure 5. Achievement of risk-based SMKP audit effectiveness indicators against HPI control targets

3.3. Discussion

The baseline analysis of SMKP compliance is conducted to assess the extent to which mining safety management documents and implementation have been applied to loading-hauling-dumping activities. At the initial audit stage, several compliance aspects still require strengthening, particularly hazard identification and risk assessment documents that do not fully cover all HPI scenarios. Some SOPs are available, but their field implementation effectiveness has not been adequately tested. Inspection checklists also tend to remain administrative and are not specifically directed toward verification of critical controls for fatal-risk prevention.

The HPI baseline is used to obtain an initial picture of event patterns that may lead to fatality or serious injury. The analysis classifies events by activity type, incident type, event time, location, involved units, failed controls, and root causes. If most HPI events occur during hauling activities, the audit should place greater examination weight on haul roads, traffic management, operator fatigue, speed control, and maintenance condition of units.

The baseline analysis of critical controls is conducted to assess whether the controls that have been established can truly prevent HPI. In a risk-based SMKP audit, the existence of control documents alone is not sufficient to demonstrate that risks are controlled. Critical controls such as traffic segregation, speed control, fatigue monitoring, brake tests, berms or windrows, positive communication, and exclusion zones must not only be written in procedures, but must also be consistently implemented in daily operations.

Audit follow-up is an important element because an audit will not create real impact if its findings are not properly completed. The baseline analysis of audit follow-up examines the number of major findings, minor findings, observations, findings related to critical controls, overdue findings, and repeated findings. In risk-based auditing, administrative findings must be distinguished from findings directly related to fatality potential so that improvement resources can be directed to the most critical aspects.

The state of the art of this study lies in combining three main approaches: SMKP Minerba, risk-based audit, and critical control management. This study shifts the audit orientation from compliance audit toward risk-based audit, meaning that the audit does not only answer whether the system exists, but also assesses whether the system effectively prevents potentially fatal events. The novelty is also reflected in the integration of leading and lagging indicators and in the specific focus on loading-hauling-dumping as the center of risk exposure in open-pit coal mining.

4. Conclusion

Based on the developed research framework, the effectiveness of risk-based SMKP Minerba audit implementation in loading-hauling-dumping activities can be assessed through the integration of audit scores, critical control verification, completion of audit finding follow-up, and HPI trends. An audit is considered effective when it can identify priority HPI scenarios, detect weaknesses in critical controls, encourage appropriate corrective action, improve field supervision quality, and reduce the HPI rate. Conversely, an audit is not yet effective if it only produces document compliance without real improvement in fatal-risk control. This study positions SMKP auditing as a strategic instrument in mining safety risk control. In loading-hauling-dumping activities, risk-based auditing should prioritize traffic management, haul-road conditions, operator fatigue, dumping control, positive communication, unit roadworthiness, and critical control verification. Open-pit coal mining companies are advised to strengthen SMKP audits using a risk-based approach, develop audit checklists based on HPI scenarios, give high priority to findings related to critical controls, and ensure that finding close-out is supported by implementation evidence and field effectiveness verification.

Reference

[1] P. Bęś, et al., "Innovative technologies to improve occupational safety in high-risk sectors," *International Journal of Environmental Research and Public Health*, 2025.

[2] M. Čelebić, et al., "Development of an integrated model for open-pit-mine excavation and haulage systems," *Sustainability*, vol. 16, no. 8, p. 3156, 2024.

[3] D. Dihartawan, P. R. Rizky, and E. Ernyasih, "Gambaran proses audit Sistem Manajemen Keselamatan Pertambangan (SMKP) di PT 'X' tahun 2022," *Environmental Occupational Health and Safety Journal*, vol. 4, no. 2, pp. 54–62, 2024. https://doi.org/10.24853/eohjs.4.2.54-62

[4] M. Goli, et al., "A simulation-based risk assessment model for autonomous haulage trucks in open-pit mines," *Applied Sciences*, vol. 15, no. 17, p. 9702, 2025.

[5] M. Hao, et al., "Hazard identification, risk assessment and management of mining industry systems based on accident causation and quantitative safety analysis," *Safety Science*, 2022.

[6] International Council on Mining and Metals, *Safety performance: Benchmarking progress of ICMM company members in 2024*. ICMM, 2025.

[7] International Council on Mining and Metals, *Critical Control Management: Good Practice Guide*. ICMM, 2026.

[8] M. Jehan, N. Kamal, M. R. Lubis, and T. A. R. Putra, "Kajian hasil implementasi Sistem Manajemen Keselamatan Pertambangan Mineral dan Batubara (SMKP Minerba) melalui audit eksternal di PT Saptaindra Sejati oleh PT Adaro Indonesia," *Journal of Geosciences, Mining Engineering, and Technology*, vol. 8, no. 2, pp. 41–49, 2024.

[9] I. Milošević, A. Stojanović, Đ. Nikolić, I. Mihajlović, A. Brkić, M. Perišić, and V. Spasojević-Brkić, "Occupational health and safety performance in a changing mining environment: Identification of critical factors," *Safety Science*, 2025. https://doi.org/10.1016/j.ssci.2024.106745

[10] Mine Safety and Health Administration, *Final rule: Safety program for surface mobile equipment*. U.S. Department of Labor, 2023.

[11] Mine Safety and Health Administration, *Powered haulage safety*. U.S. Department of Labor, 2026.

[12] A. Moniri-Morad, M. S. Shishvan, M. Aguilar, M. Goli, and J. Sattarvand, "Powered haulage safety, challenges, analysis, and solutions in the mining industry: A comprehensive review," *Results in Engineering*, vol. 21, p. 101684, 2024. https://doi.org/10.1016/j.rineng.2023.101684

[13] A. S. Moreira, et al., "Physical and mental fatigue in shift work and mitigation strategies among high-capacity dump truck drivers in a coal mining operation," *International Journal of Environmental Research and Public Health*, 2025.

[14] S. A. Nugroho, et al., "Factors associated with workplace accidents among dump truck operators in coal mining," *Faletehan Health Journal*, 2024.

[15] X. Qiang, et al., "Development of targeted safety hazard management plans using association rule mining for underground mines," *Heliyon*, 2024.

[16] L. Rianti, M. P. Sari, and W. A. Putri, "Evaluation of implementation of Mining Safety Management System at PT Putra Muba Coal Sungai Lilin District Musi Banyuasin Regency South Sumatera Province," in *Proceedings of the International Conference on Sustainable Engineering and Technology*, pp. 499–512, 2024. https://doi.org/10.2991/978-94-6463-386-3_51

[17] P. W. Rondonuwu and Z. E. Tamod, "Evaluasi penerapan Sistem Manajemen Keselamatan Pertambangan (SMKP) dan Sistem Pengelolaan Perlindungan Lingkungan Hidup Pertambangan (SPPLHP) di PT Sumber Energi Jaya," *Agri-SosioEkonomi*, vol. 17, no. 2, pp. 703–710, 2021. https://doi.org/10.35791/agrsosek.17.2MDK.2021.35438

[18] M. A. H. Salasa, E. S. Sumitro, A. Alfianto, K. Anam, and A. Y. Pramono, "Penilaian kinerja keselamatan pertambangan di PT Putra Perkasa Abadi: Dampak implementasi Sistem Manajemen Keselamatan Pertambangan (SMKP) terhadap kesehatan dan keselamatan kerja," *Jurnal Sosial Teknologi*, vol. 4, no. 11, pp. 980–987, 2024. https://doi.org/10.59188/jurnalsostech.v4i11.27627

[19] D. Saputra, Y. Ashari, and Aviasti, "Penerapan Sistem Manajemen Keselamatan Pertambangan di tambang andesit PT Gunung Kulalet Bandung," *Jurnal Riset Teknik Pertambangan*, vol. 3, no. 1, pp. 35–40, 2023. https://doi.org/10.29313/jrtp.v3i1.2109

[20] A. Susanto, S. Hania, N. J. Wijoyo, W. Kurniawan, W. Wiyarta, S. C. Budi, Y. Pane, and D. B. Prasetio, "Implementasi Sistem Manajemen Keselamatan Pertambangan di sektor Minerba Indonesia: Tinjauan literatur sistematis," *Jurnal Kesehatan*, vol. 18, no. 1, pp. 1–10, 2025. https://doi.org/10.32763/yzppp082

[21] H. K. Wardani, E. Nursanto, and N. A. Amri, "Penerapan Sistem Manajemen Keselamatan Pertambangan (SMKP) di perusahaan pertambangan guna meningkatkan kinerja keselamatan operasi dan kesehatan dan keselamatan kerja," *Syntax Literate: Jurnal Ilmiah Indonesia*, vol. 7, no. 4, 2022. https://doi.org/10.36418/syntax-literate.v7i4.6678

DOI: https://doi.org/10.31004/riggs.v5i2.8505