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Geological Risk Assessment, Environmental Management Practices, and Sustainable Mining Operations: Evidence from a Survey-Based SEM-PLS

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Abstract

The mining industry faces significant challenges in maintaining sustainable operations due to geological uncertainty, environmental degradation, and increasing demands for effective environmental management. Geological hazards such as slope instability, landslide potential, groundwater inflow, mine drainage problems, erosion, and waste rock instability may directly affect environmental quality and operational sustainability. This study examines the relationships among Geological Risk Assessment (GRA), Environmental Management Practices (EMP), and Sustainable Mining Operations (SMO) using survey responses from 150 mining professionals in Indonesia, covering coal, nickel, copper, and gold mines. A cross-sectional survey design and Structural Equation Modeling–Partial Least Squares (SEM-PLS) were applied to assess the associations among GRA, EMP, and SMO and to evaluate the mediating role of EMP. The results indicate that GRA is positively associated with EMP ($\beta = 0.718$) and SMO ($\beta = 0.402$), while EMP positively affects SMO ($\beta = 0.424$). EMP also partially mediates the relationship between GRA and SMO, with an indirect effect of $\beta = 0.305$. These findings suggest that geological risk assessment contributes to sustainable mining by strengthening environmental management practices, particularly in relation to mine water management, erosion control, land reclamation, waste management, and environmental impact monitoring. The study provides a conceptual SEM-PLS model linking geological risk, environmental management, and sustainable mining performance, offering practical insights for improving environmentally responsible mining operations in Indonesia.

Keywords: environmental management practices, geological risk assessment, mine water management; mining sustainability, sem-pls, sustainable mining operations

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INTRODUCTION

The mining industry plays a critical role in global and national economic development by providing essential raw materials, creating employment opportunities, and generating significant revenue for governments (Bibri, 2024). While large-scale mining operations support industrial growth, they also produce complex environmental, social, and technical challenges that require careful and sustainable management (Almusaed, 2024). Modern mining enterprises are increasingly expected to achieve not only production targets but also environmental protection, occupational safety, and sustainable resource utilization. Consequently, mining companies must integrate sustainability principles across exploration, extraction, processing, and closure phases, making operational risk management a key determinant of long-term organizational success (Jovanović, Stanković, & Krstić, 2023). Successfully managing these risks enables companies to maintain operational continuity while supporting sustainable development goals.

Geological risk is a primary factor influencing operational performance and safety in mining activities. Mines operate in geologically complex areas where slope instability, pit wall failure, subsidence, acid mine drainage, groundwater inflow, seismicity, and waste rock instability can threaten both human safety and production efficiency (Almusaed, 2024). Accurate assessment of these geological hazards is essential for minimizing financial losses, preventing environmental damage, and safeguarding workers. Geological Risk Assessment (GRA) provides critical data for decision-making, such as identifying suitable locations for waste dumps, designing slope stabilization structures, implementing erosion control measures, managing mine water systems, mitigating tailings risks, and planning land reclamation (Gang, 2024; Trivedi, 2025). In this regard, GRA not only serves as a technical tool but also underpins the planning and implementation of effective Environmental Management Practices (EMP).

Environmental management is a core element of sustainable mining operations, encompassing mine waste management, water and air quality monitoring, erosion control, land reclamation, and ecosystem protection. Effective EMP reduces the ecological footprint of mining activities, enhances public and regulatory acceptance, and ensures compliance with environmental laws and standards (Babaei, 2024; Hoyle, 2024). Integrating GRA into EMP ensures that environmental management decisions are informed by geological realities, thereby improving operational efficiency and sustainability outcomes. For instance, the placement of tailings storage facilities or waste rock dumps is directly influenced by slope stability and subsurface hydrology data, demonstrating how geological insights are operationalized within EMP frameworks (Hong, 2024). This integration ensures that environmental management decisions are technically sound and aligned with operational safety requirements.

Despite extensive research on geological risk and environmental management independently, empirical evidence examining how GRA impacts Sustainable Mining Operations (SMO) through EMP remains limited, especially in developing countries such as Indonesia (Hong, 2024; Zahoor et al., 2020). Previous studies primarily focus on technical dimensions, including rock mechanics, slope stability, and geotechnical hazard mitigation, which underscores the importance of understanding geological conditions and failure mechanisms prior to operational decision-making in mining engineerin (Tiedeu et al., 2024), while the mediating function of EMP has received comparatively little attention. This gap highlights the need for integrative models that simultaneously account for geological risk, environmental practices, and sustainability outcomes. The lack of such models constrains comprehensive understanding and limits the ability of managers to make evidence-based decisions that balance technical, environmental, and social considerations.

The theoretical foundation of this study draws on Risk Management Theory, Sustainability Theory, and the Natural Resource-Based View (NRBV). Risk Management Theory posits that systematic identification, analysis, and mitigation of risks reduce uncertainty and enhance organizational performance (Trivedi, 2025). In the mining context, GRA represents a crucial source of operational uncertainty that, if unmanaged, can compromise environmental, economic, and safety outcomes. Sustainability Theory emphasizes that organizational sustainability encompasses economic, environmental, and social performance simultaneously, requiring integrated management strategies (Haghighizadeh, 2024). NRBV suggests that effective management of natural resources and environmental capabilities can confer sustainable competitive advantages by improving long term operational performance and ecological outcomes (Appannan et al., 2020; Taddei, 2024). Together, these theoretical perspectives justify examining the direct and indirect linkages among GRA, EMP, and SMO.

Empirically, developing countries present distinct challenges compared to developed nations, including variability in geological conditions, regulatory frameworks, technological capacity, and governance quality. Studies focusing on Indonesian mines indicate that differences in mine types, operational scales, and local environmental conditions produce heterogeneous risk profiles (Hong, 2024). Consequently, an integrative model that captures the mediating role of EMP across various mine types and locations can provide deeper insights into operational sustainability and guide more effective risk-informed environmental decision-making.

This study aims to investigate the influence of Geological Risk Assessment on Environmental Management Practices and Sustainable Mining Operations, as well as the mediating role of Environmental Management Practices. The research questions guiding this study are: (1) Does GRA significantly affect EMP? (2) Do EMP significantly affect SMO? (3) Does GRA have a direct effect on SMO? (4) Does EMP mediate the relationship between GRA and SMO? Accordingly, the hypotheses are: H1: GRA positively affects EMP; H2: EMP positively affects SMO; H3: GRA positively affects SMO; H4: EMP mediates the effect of GRA on SMO. By addressing these questions, the study contributes to the mining sustainability literature by providing empirical evidence of the mechanisms linking geological risk, environmental management, and operational sustainability. The findings are expected to inform both theoretical understanding and practical decision-making in modern mining management.

METHOD

Research Design

This study employed a cross-sectional explanatory survey design to examine the relationships among Geological Risk Assessment (GRA), Environmental Management Practices (EMP), and Sustainable Mining Operations (SMO). The research model was developed based on the conceptual framework presented in **Figure 1**, which illustrates the hypothesized relationships among the three main constructs and the role of EMP as a mediating variable. The framework proposes that GRA directly influences EMP and SMO, while EMP directly influences SMO and mediates the relationship between GRA and SMO.

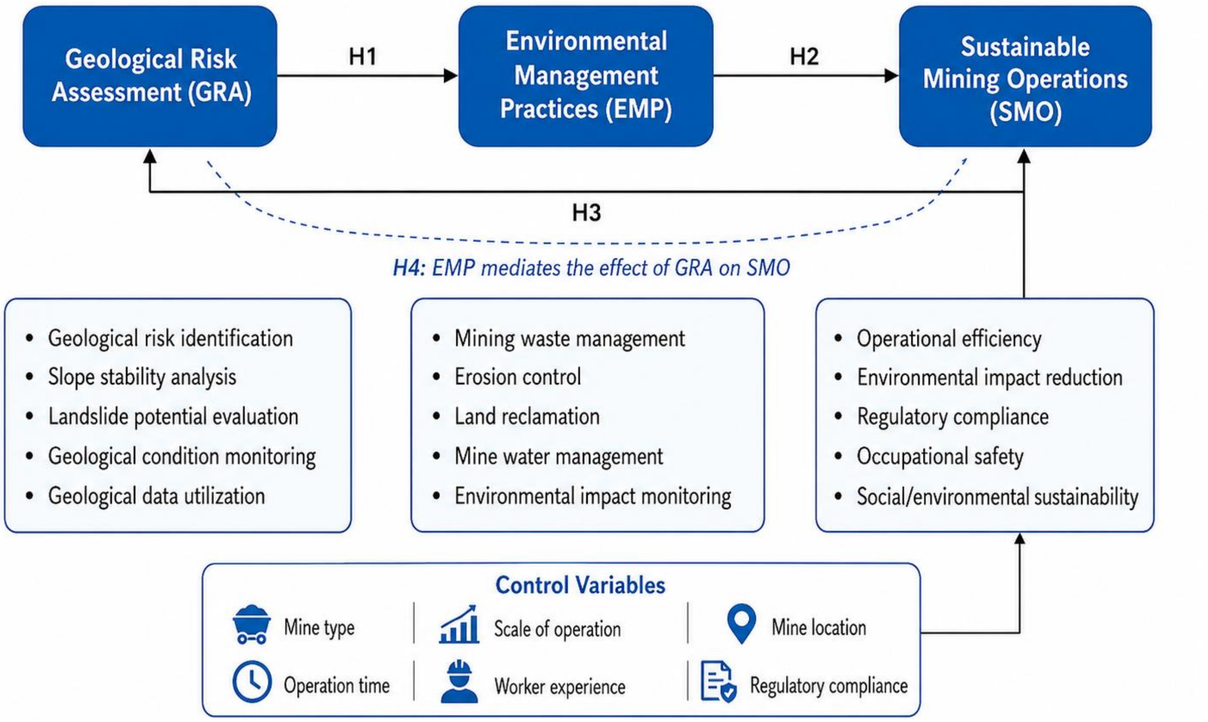

Figure 1. Conceptual framework of the relationships among Geological Risk Assessment, Environmental Management Practices, and Sustainable Mining Operations

Structural Equation Modeling–Partial Least Squares (SEM-PLS) was used to test the proposed model. SEM-PLS was selected because it is suitable for analyzing complex relationships among latent constructs, especially in models involving mediation and perception-based survey data. This method is also appropriate for studies with relatively moderate sample sizes and does not require strict assumptions of multivariate normality. The conceptual basis of the model is grounded in Risk Management Theory, Sustainability Theory, and the Natural Resource-Based View (NRBV), which together explain how geological risk assessment and environmental management capabilities contribute to sustainable mining operations.

Participants

The research population included individuals involved in mining operational and management activities, namely mine managers, operational supervisors, geological staff, and environmental staff. A total of 150 respondents were recruited from multiple mining companies across Indonesia, covering a range of mine types and locations. Purposive sampling was applied with inclusion criteria: at least one year of work experience in the mining sector and a clear understanding of company operations and environmental management processes. Participation was voluntary, confidentiality was guaranteed, and ethical approval was obtained from the relevant institutional review board. Informed consent was obtained from all participants before data collection. To ensure proper model estimation, control variables included mine type, scale of operations, mine location, length of mine operation, worker experience, and regulatory compliance (Radebe & Chipangamate, 2024). Categorical variables (e.g., mine type and location) were dummy coded, while continuous variables were treated numerically.

Measurement Items

Data were collected through a structured questionnaire using a five-point Likert scale (1 = strongly disagree to 5 = strongly agree). Each construct was measured using five indicators. **Table 1** presents the measurement items, codes, and indicators. All items were adapted from prior research in mining and environmental sustainability, ensuring content validity.

Table 1. Measurement Items for Constructs

Construct	Code	Indicator
Geological Risk Assessment	GRA1	Geological risk identification
	GRA2	Slope stability analysis
	GRA3	Landslide potential evaluation
	GRA4	Geological condition monitoring
	GRA5	Geological data utilization
Environmental Management Practices	EMP1	Mining waste management
	EMP2	Erosion control
	EMP3	Land reclamation
	EMP4	Mine water management
	EMP5	Environmental impact monitoring
Sustainable Mining Operations	SMO1	Operational efficiency
	SMO2	Environmental impact reduction
	SMO3	Regulatory compliance
	SMO4	Occupational safety
	SMO5	Social/environmental sustainability

The selected indicators represent each construct comprehensively, as supported by prior literature. For example, SMO includes operational efficiency, environmental impact reduction, regulatory compliance, occupational safety, and social/environmental sustainability, reflecting a multidimensional view of sustainable mining operations. These indicators were reviewed by domain experts for content validity and are consistent with existing research.

Control Variables

Several control variables were included to improve the accuracy of the structural model. These variables consisted of mine type, scale of operation, mine location, operation time, worker experience, and regulatory compliance. Mine type and mine location were treated as categorical variables and coded accordingly, while operation time and worker experience were treated as numerical variables. The inclusion of these control variables was intended to account for differences in operational characteristics that may influence Sustainable Mining Operations.

Data Analysis

Data analysis was conducted using Structural Equation Modeling–Partial Least Squares with SmartPLS software. The analysis was carried out in two main stages: evaluation of the measurement model and evaluation of the structural model. The measurement model was evaluated using outer loading, Average Variance Extracted (AVE), Composite Reliability, Cronbach's Alpha, rho_A, and Heterotrait-Monotrait Ratio (HTMT). Outer loading values above 0.70 were considered acceptable. AVE values above 0.50 indicated adequate convergent validity, while Composite Reliability and Cronbach's Alpha values above 0.70 indicated acceptable internal consistency. HTMT values below 0.90 were used to confirm discriminant validity among constructs.

The structural model was evaluated using Variance Inflation Factor (VIF), coefficient of determination (R^2), effect size (f^2), predictive relevance (Q^2), and path coefficient analysis. VIF values were used to assess multicollinearity among predictor variables. R^2 values were used to evaluate the explanatory power of the model, while f^2 values were used to assess the effect size of each relationship. Q^2 values were used to evaluate the predictive relevance of the endogenous constructs.

Hypothesis testing was performed using a bootstrapping procedure with 5,000 subsamples. A hypothesis was accepted when the t-statistic was greater than 1.96 and the p-value was less than 0.05. The mediating role of Environmental Management Practices in the relationship between Geological Risk Assessment and Sustainable Mining Operations was examined through the specific indirect effect. Because both the direct effect of GRA on SMO and the indirect effect through EMP were tested, the mediation type was determined based on the significance of both paths.

RESULTS AND DISCUSSION

The analysis was conducted using Structural Equation Modeling–Partial Least Squares (SEM-PLS) to evaluate both the measurement and structural models. The study began by examining respondent characteristics and descriptive statistics. The characteristics of the respondents are summarized in **Table 1.**

Table 1. Respondent Characteristics

Characteristics	Category	Frequency	Percentage (%)
Types of Mines	Coal	44	29.3
	Nickel	41	27.3
	Copper	34	22.7
	Gold	31	20.7
Scale of Operation	Big	62	41.3
	Small	45	30.0
	Intermediate	43	28.7
Mine Location	Papua	34	22.7
	Kalimantan	31	20.7
	Sulawesi	30	20.0
	Java	30	20.0
	Sumatra	25	16.7
Regulatory Compliance Level	Low (2)	41	27.3
	Medium (3)	47	31.3
	Height (4)	26	17.3
	Very High (5)	36	24.0

The distribution of respondents shows that mining activities in this study were dominated by the coal sector with 44 respondents or 29.3%, followed by the nickel sector with 41 respondents or 27.3%. Respondents from the copper and gold sectors numbered 34 respondents (22.7%) and 31 respondents (20.7%), respectively. Based on the scale of operations, most mining companies were categorized as large with 62 respondents or 41.3%, while the small and medium categories were 45 respondents (30.0%) and 43 respondents (28.7%), respectively. The distribution of mining locations was relatively even with the highest concentration in Papua at 22.7%, followed by Kalimantan at 20.7%, Sulawesi and Java each at 20.0%, and Sumatra at 16.7%. The level of regulatory compliance showed that the majority of respondents were in the medium category at 31.3%, followed by the low category at 27.3%, very high at 24.0%, and high at 17.3%. This composition illustrates that the research sample has covered a variety of operational characteristics so that it is able to provide a representative picture of the conditions of the mining industry being studied. Descriptive statistics for the research variables are presented in **Table 2**.

Table 2. Descriptive Statistics of Research Variables

Variables	Mean	Standard Deviation	Minimum	Maximum
Geological Risk Assessment (GRA)	3.687	0.723	2.000	5.000
Environmental Management Practices (EMP)	3.572	0.605	2.000	5.000
Sustainable Mining Operations (SMO)	3.799	0.543	2.200	5.000

Descriptive statistics indicate that all research variables have an average above the midpoint of the measurement scale. Sustainable Mining Operations obtained the highest average value of 3.799 with a standard deviation of 0.543, indicating that sustainable mining operations practices have been implemented at a relatively good level and respondents' perceptions tend to be homogeneous. Geological Risk Assessment had an average value of 3.687 with a standard deviation of 0.723, indicating that geological risk identification, evaluation, and monitoring activities have been carried out quite intensively although there are still variations in perceptions between respondents (Chu et al., 2020). Environmental Management Practices obtained an average value of 3.572 with a standard deviation of 0.605, indicating a good level of environmental management implementation in mining companies (Cai et al., 2024). The range of minimum and maximum values between 2,000 and 5,000 indicates a variation in respondents' answers without any indication of extreme values that could potentially interfere with the analysis. Overall, the descriptive results indicate that the three main constructs are in the medium to high category. The outer loadings of all constructs are shown in **Table 3**.

Table 3. Outer Loading

Construct	Indicator	Loading
	GRA1	0.887
	GRA2	0.864
Geological Risk Assessment	GRA3	0.862
	GRA4	0.862
	GRA5	0.848
	EMP1	0.839
	EMP2	0.834
Environmental Management Practices	EMP3	0.822
	EMP4	0.832
	EMP5	0.827
	SMO1	0.803
	SMO2	0.789
Sustainable Mining Operations	SMO3	0.810
	SMO4	0.795
	SMO5	0.801

After reviewing **Table 3**, it is evident that all indicators exceed the recommended threshold of 0.70, confirming adequate convergent validity. In the Geological Risk Assessment construct, loading values range from 0.848 to 0.887, with GRA1 demonstrating the strongest contribution. Environmental Management Practices indicators range from 0.822 to 0.839, showing that all aspects of environmental management are consistently captured. Sustainable Mining Operations indicators range from 0.789 to 0.810, confirming that the construct is measured reliably across all its dimensions.

The relatively high loading values for all indicators indicate that each item effectively represents its latent construct. Practically, the high loading of GRA1 suggests that risk identification is a particularly critical element in geological risk assessment, providing essential input for decision-making in environmental management and sustainable operations (Bini et al., 2018). Overall, these results demonstrate that the measurement model is robust and suitable for subsequent structural analysis in SEM-PLS. Reliability and validity results for all constructs are provided in **Table 4**.

Table 4. Construct Reliability and Validity

Construct	Cronbach's Alpha	rho_A	Composite Reliability	AVE
Geological Risk Assessment	0.916	0.916	0.937	0.747
Environmental Management Practices	0.888	0.888	0.918	0.691
Sustainable Mining Operations	0.881	0.884	0.913	0.678

Reliability and construct validity evaluations indicate that all research variables meet the criteria required in the SEM-PLS analysis. Geological Risk Assessment has a Cronbach's Alpha value of 0.916, Composite Reliability of 0.937, and AVE of 0.747. Environmental Management Practices obtained a Cronbach's Alpha value of 0.888, Composite Reliability of 0.918, and AVE of 0.691. Sustainable Mining Operations showed a Cronbach's Alpha value of 0.881, Composite Reliability of 0.913, and AVE of 0.678. All Composite Reliability values were well above the minimum limit of 0.70, while all AVE values exceeded the 0.50 criterion. These findings confirm that the research instrument has an excellent level of internal consistency and is able to adequately explain the indicator variance. Thus, all constructs can be declared reliable and meet convergent validity. Discriminant validity evaluated via HTMT is shown in **Table 5**.

Table 5. HTML Values

Construct	GRA	EMP	SMO
Geological Risk Assessment (GRA)	-	0.796	0.793
Environmental Management Practices (EMP)	0.796	-	0.805
Sustainable Mining Operations (SMO)	0.793	0.805	-

Discriminant validity testing using the Heterotrait-Monotrait Ratio approach shows that all HTMT values are below the maximum limit of 0.90. The HTMT value between Geological Risk Assessment and Environmental Management Practices is 0.796, between Geological Risk Assessment and Sustainable Mining Operations is 0.793, and between Environmental Management Practices and Sustainable Mining Operations is 0.805. These results indicate that each construct has distinct characteristics and does not experience conceptual overlap. HTMT values below the threshold indicate that each latent variable is able to explain different phenomena despite still having a close relationship in the research model (Ropero et al., 2014). This condition strengthens the quality of the measurement model that has been built. Thus, the discriminant validity in this study can be declared to be adequately fulfilled. Multicollinearity among predictor variables was assessed using the Variance Inflation Factor (VIF), as presented in **Table 6**.

Table 6. Inner VIF

Relationship	VIF
GRA → EMP	1,062
GRA → SMO	1.058
EMP → SMO	1.041
Mine type → SMO	1.034
Regulatory compliance → SMO	1.029
Operation time → SMO	1.037
Mine location → SMO	1.032

Relationship	VIF
Worker experience → SMO	1.026
Scale of operation → SMO	1.030

Multicollinearity testing using the Variance Inflation Factor (VIF) value yielded a VIF of 1.062 for the relationship between Geological Risk Assessment and Environmental Management Practices. This value is well below the recommended maximum limit of 5.00. This result indicates that there are no collinearity issues between variables in the structural model used. The low VIF value indicates that the independent variables do not have excessive correlations with other variables, allowing accurate path coefficient estimation. This condition also demonstrates that the research model has good stability for use in hypothesis testing. The presence of low multicollinearity provides confidence that the estimation results are not distorted due to excessively strong linear relationships between variables. The explanatory power of the model is presented in **Table 7**.

Table 7. Coefficient of Determination (R^2)

Endogenous Variables	R^2	R^2 Adjusted
Environmental Management Practices	0.515	0.512
Sustainable Mining Operations	0.622	0.600

The model's ability to explain endogenous variables is demonstrated through the coefficient of determination. Environmental Management Practices has an R^2 value of 0.515, meaning that 51.5% of the variation in environmental management practices can be explained by the Geological Risk Assessment. Sustainable Mining Operations obtained an R^2 value of 0.622, indicating that 62.2% of the variation in sustainable mining operations can be explained by the variables contained in the research model. This value is included in the moderate to strong category, indicating good predictive ability of the model. The remainder is influenced by other factors outside the model that were not analyzed in this study. The high R^2 value indicates that the constructed structural relationship has adequate explanatory power regarding the phenomenon studied. This finding strengthens the model's relevance in explaining the sustainability of mining operations. Effect sizes (f^2) are summarized in **Table 8**.

Table 8. Effect Size (f^2)

Relationship	f^2
GRA → EMP	1,062
EMP → SMO	0.325
GRA → SMO	0.167
Control variables → SMO	0.010–0.025

The significant influence of Geological Risk Assessment on Environmental Management Practices is demonstrated by the effect size value of 1.062. This value far exceeds the recommended large category limit of 0.35. This finding indicates that the presence of the Geological Risk Assessment variable makes a very strong contribution to changes in Environmental Management Practices. This significant influence indicates that improving the quality of geological risk identification, evaluation, and monitoring will have direct implications for improving environmental management practices (Bini et al., 2018). The large effect size also indicates that the independent variable plays a central role in the research model. This condition emphasizes the importance of geological risk management as a basis for implementing effective environmental management in the mining sector. Predictive relevance (Q^2) is shown in **Table 9**.

The results of the predictive relevance test indicate that all endogenous variables have positive Q^2 values. Environmental Management Practices obtained a Q^2 value of 0.344, while Sustainable Mining Operations obtained a Q^2 value of 0.407. These values indicate that the model has good predictive ability regarding the observed data. A higher Q^2 value indicates a better model's ability to reconstruct the observed empirical data. These results indicate that the model is not only able to explain the relationships between variables theoretically but also has adequate predictive power. Good predictive ability strengthens the quality of the structural model used in the study. Therefore, the research model is considered suitable for use in explaining the phenomenon of sustainable mining operations. Path coefficients and mediation analysis are presented in **Table 10**.

Table 9. Predictive Relevance (Q^2)

Construct	Q^2
Environmental Management Practices	0.344
Sustainable Mining Operations	0.407

Table 10. Path Coefficients and Hypothesis Testing and Specific Indirect Effect (Mediation)

Hypothesis	Connection	β	T Statistics	P Values	Decision
H1	GRA → EMP	0.718	17.026	0.000	Accepted
H2	EMP → SMO	0.424	5.369	0.000	Accepted
H3	GRA → SMO	0.402	5.123	0.000	Accepted
H4	GRA → EMP → SMO	0.305	5.188	0.000	Accepted

Path coefficient analysis shows that all research hypotheses are accepted. The effect of Geological Risk Assessment on Environmental Management Practices has a coefficient of 0.718 with a t-statistic value of 17.026 and a p-value of 0.000, indicating a positive and significant relationship. Environmental Management Practices also have a positive effect on Sustainable Mining Operations with a coefficient of 0.424, a t-statistic value of 5.369, and a p-value of 0.000. The direct effect of Geological Risk Assessment on Sustainable Mining Operations shows a coefficient of 0.402 with a t-statistic value of 5.123 and a p-value of 0.000. Mediation testing produces an indirect effect coefficient of 0.305 with a t-statistic value of 5.188 and a p-value of 0.000. These findings indicate that Environmental Management Practices are able to significantly mediate the relationship between Geological Risk Assessment and Sustainable Mining Operations. Total effects are shown in **Table 11**.

Table 11. Total Effects

Relationship	Total Effect
GRA → EMP	0.718
GRA → SMO	0.707
EMP → SMO	0.424
Note: Total effect of GRA on SMO = Direct Effect (0.402) + Indirect Effect (0.305) = 0.707.	

The total effects evaluation shows that Geological Risk Assessment has a total effect of 0.707 on Sustainable Mining Operations. This value is a combination of a direct effect of 0.402 and an indirect effect through Environmental Management Practices of 0.305. The large total effect value indicates that improving geological risk management will have a substantial impact on the sustainability of mining operations. The effect of Geological Risk Assessment on Environmental Management Practices remains the strongest relationship in the model with a value of 0.718. Environmental Management Practices also maintain a positive effect on Sustainable Mining Operations with a total effect value of 0.424. These findings confirm that environmental management practices play a crucial role in linking geological risk management to the success of sustainable mining operations. Control variable effects are presented in **Table 12**.

Testing of control variables shows that only the type of mine has a significant influence on Sustainable Mining Operations with a coefficient of -0.119, a t-statistic value of 2.199, and a p-value of 0.028. These results indicate that the characteristics of mining commodities can influence the level of sustainability of operations carried out by a company. The variables of regulatory compliance, length of operation, mine location, worker experience, and scale of operation do not show a significant influence because they have a p-value above 0.05. This condition indicates that these factors do not provide a strong enough contribution in explaining the variation of Sustainable Mining

Operations in this research model. The dominant influence of the main variables compared to the control variables indicates that geological risk aspects and environmental management practices are more determining factors in creating sustainable mining operations. This finding strengthens the research focus on the relationship between the main variables that have been built in the conceptual model.

Table 12. Control Variables on Sustainable Mining Operations

Control Variables	β	T Statistics	P Values	Decision
Types of Mines	-0.119	2,199	0.028	Significant
Regulatory Compliance	-0.008	0.167	0.868	Not Significant
Operation Time	-0.079	1,491	0.137	Not Significant
Mine Location	0.003	0.050	0.961	Not Significant
Worker Experience	0.042	0.750	0.453	Not Significant
Scale of Operation	0.032	0.573	0.567	Not Significant

The **Figure 2** displays a Partial Least Squares Structural Equation Modeling (PLS-SEM) model that analyzes the determinants of Sustainable Mining Operations (SMO). The estimation results show that the Environmental Management Practices (EMP) variable has the largest positive influence on SMO with a path coefficient of 0.424, followed by Geological Risk Assessment (GRA) which has a direct influence of 0.402 and a strong indirect influence on EMP of 0.718. Collectively, this model successfully explains 62.2% of the SMO variance (R^2 = 0.622) and 51.5% of the EMP variance (R^2 = 0.515), indicating a substantial level of predictive accuracy. Meanwhile, all reflective indicators in each latent variable (GRA1–GRA5, EMP1–EMP5, SMO1–SMO5) have outer loading values above 0.79, proving excellent convergent validity. On the other hand, the six control variables in the form of operational characteristics and mine compliance at the bottom only have a very small marginal impact and tend to be insignificant on the sustainability of mine operations.

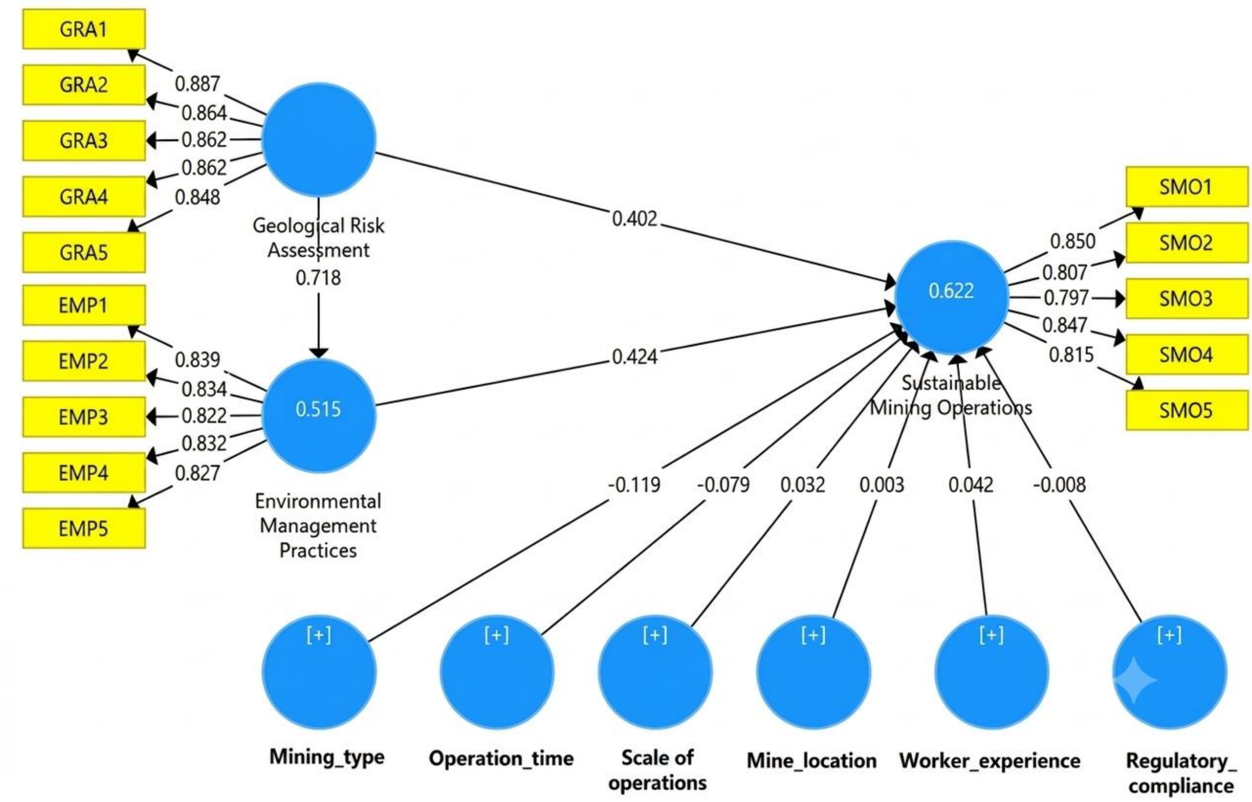

Figure 2. PLS-SEM path diagram showing the relationships among Geological Risk Assessment, Environmental Management Practices, and Sustainable Mining Operations

The findings of this study confirm significant relationships among Geological Risk Assessment (GRA), Environmental Management Practices (EMP), and Sustainable Mining Operations (SMO), highlighting the foundational role of geological risk assessment in guiding environmental management in mining. The path coefficient of 0.718 for GRA → EMP indicates a strong positive association, demonstrating that companies with more effective geological risk identification, slope stability analysis, landslide potential evaluation, geological condition monitoring, and utilization of geological data implement stronger and more comprehensive environmental management practices. Practically, this relationship suggests that high-quality GRA enables mining managers to design more effective waste dump layouts, implement precise erosion control measures, optimize mine water management, plan reclamation activities efficiently, and utilize GIS and remote sensing technologies to monitor geotechnical risks, ensuring that environmental policies are informed by accurate geological information. These results emphasize that geological risk management serves not only to mitigate operational and safety threats but also as a strategic resource for achieving sustainable mining practices, linking technical risk evaluation directly to improved environmental outcomes (Dalbanjan, 2024; Lahlali, 2024).

EMP was also found to have a significant positive association with SMO ($\beta = 0.424$), confirming that robust environmental management practices contribute directly to sustainable operational outcomes. Effective EMP—including mine waste management, erosion control, land reclamation, mine water management, and environmental impact monitoring—supports increased operational efficiency, regulatory compliance, occupational safety, and social and environmental sustainability. The effect size ($f^2 = 0.325$) indicates a moderate to large influence, emphasizing that environmental management is a central driver of operational sustainability rather than a mere compliance requirement. These findings demonstrate that integrating EMP into day-to-day mining operations, supported by geospatial tools like GIS and remote sensing, enhances the ability to link geological risk data directly to reclamation and water management strategies (Batool, 2024; Ejiohuo, 2025). This integration allows mining companies to make informed, evidence-based operational decisions that improve environmental outcomes and long-term sustainability.

The direct relationship between GRA and SMO ($\beta = 0.402$) further illustrates that companies with superior geological risk capabilities tend to operate more sustainably. Well-identified and managed geological hazards reduce operational disruptions, optimize resource use, and enhance workplace safety, ensuring that production processes are maintained with minimal interruptions. The partial mediation of EMP (indirect effect = 0.305) confirms that the benefits of GRA are amplified when translated into effective environmental management practices, highlighting that technical risk assessment alone is insufficient to achieve full sustainability outcomes. Companies that convert geological insights into actionable EMP achieve higher sustainability performance than those focusing solely on hazard mitigation, as these practices enable systematic planning of waste disposal, erosion control, mine water management, and reclamation activities. Integrating geological data into day-to-day environmental management decisions also facilitates the use of geospatial technologies such as GIS and remote sensing to monitor slope stability, tailings storage, and water quality, providing operational teams with timely information to adjust management interventions. Overall, these findings demonstrate that environmental management serves as a crucial mechanism linking risk assessment to operational sustainability, ensuring that geological risk information directly contributes to long-term ecological, social, and economic outcomes in mining operations (Sun & Ye, 2021).

The explanatory power of the model is substantial, with R^2 values of 0.515 for EMP and 0.622 for SMO, indicating that GRA and the included control variables explain a significant portion of the variance in environmental management practices and sustainable operations. Predictive relevance (Q^2) values of 0.344 for EMP and 0.407 for SMO support the model's ability to predict observed outcomes, demonstrating practical utility for managerial decision-making. The very large effect size for GRA → EMP ($f^2 = 1.062$) reinforces the dominant influence of geological risk assessment on environmental management. Analysis of control variables shows that only mine type significantly influences SMO ($\beta = -0.119$), suggesting that certain commodities present inherent challenges affecting sustainability performance, likely due to differences in geological characteristics, mining methods, and operational risk profiles. Other variables—regulatory compliance, length of operation, mine location, worker experience, and scale of operation—were not significant, reinforcing that sustainable mining is primarily driven by the effective implementation of geological risk management and environmental practices (Fletcher, 2024; Caro, 2024). This highlights that companies should prioritize geological risk assessment and environmental management initiatives over administrative or demographic factors to achieve long-term operational sustainability.

From a theoretical perspective, these findings reinforce Risk Management Theory by demonstrating that systematic risk identification and mitigation are essential for sustainable operational performance. The study extends the literature by showing that GRA benefits are maximized when mediated by EMP, providing empirical evidence that links technical risk assessment with environmental and sustainability outcomes. This integration advances understanding of how mining companies can strategically leverage geological information to enhance operational sustainability (Dalbanjan, 2024; Batool, 2024). These insights suggest that incorporating geological risk data into environmental management frameworks can strengthen both theoretical models and practical decision-making in mining operations.

The practical implications for mining companies are clear: organizations should strengthen geological risk assessment systems as part of broader sustainability strategies, develop geotechnical monitoring capacities, and utilize GIS and remote sensing technologies for risk mapping to enhance operational decision-making. It is essential that geological risk data be systematically translated into actionable environmental management policies, ensuring that risk insights inform waste management, erosion control, water management, and reclamation planning at the operational level. Public policies should encourage the integration of geological risk assessment with environmental standards during licensing and operational oversight to support long-term environmental and social sustainability (Ejiohuo, 2025; Seketi & Sundari, 2026). Such regulatory and operational integration enables mining companies to proactively reduce environmental impacts, optimize resource use, and achieve sustainable performance while maintaining compliance with both technical and social requirements.

This study has several limitations. The cross-sectional survey design relies on perception-based data rather than objective operational measurements, limiting causal inferences. The sample, although diverse, is geographically constrained and focused on certain mine types, potentially limiting generalizability. Instrument validation was conducted through expert review and statistical assessment, but may not capture all dimensions of the constructs. Future research should expand the study area, include more diverse mine types, employ longitudinal designs to observe changes in relationships over time, and integrate variables such as mining technology innovation, safety culture, corporate governance, and stakeholder engagement to enhance the predictive power and practical applicability of the model (Islam, 2024). Such expansions will enable a more comprehensive understanding of the dynamic interactions between geological risk, environmental management, and sustainable mining outcomes, providing stronger guidance for both researchers and industry practitioners.

CONCLUSION

This study demonstrates that Geological Risk Assessment plays an important role in supporting Sustainable Mining Operations, both directly and indirectly through Environmental Management Practices. The findings show that better geological risk identification, slope stability analysis, landslide potential evaluation, geological condition monitoring, and geological data utilization are associated with stronger environmental management practices. These practices include mine waste management, erosion control, land reclamation, mine water management, and environmental impact monitoring. Environmental Management Practices were found to partially mediate the relationship between Geological Risk Assessment and Sustainable Mining Operations. This indicates that geological risk assessment contributes to sustainability not only by reducing operational uncertainty but also by strengthening environmental protection strategies. The results highlight the importance of integrating geological risk information into environmental management systems to reduce land degradation, control erosion and sedimentation, manage mine water, prevent environmental pollution, and support regulatory compliance. The main contribution of this study is the development of a survey-based SEM-PLS model that links geological risk assessment, environmental management, and sustainable mining operations in the Indonesian mining context. The model provides a practical framework for mining companies and regulators to understand how geological risk assessment can support environmentally responsible mining. From a sustainability perspective, mining companies should ensure that geological risk assessment is directly connected to environmental planning, mine water management, reclamation programs, and long-term environmental monitoring. This study is limited by its cross-sectional design and reliance on perception-based survey data. Future research should include longitudinal analysis, objective environmental performance indicators, water quality data, mine drainage characteristics, reclamation success indicators, and field-based geological risk assessment. Further studies may also integrate hydrological modeling, GIS-based environmental risk mapping, and life-cycle sustainability assessment to strengthen the environmental relevance of sustainable mining research.

AUTHOR CONTRIBUTIONS

Conceptualization, OP and RA; methodology, OP, RA, and ZP; software, RA and ZP; validation, OP and RA; formal analysis, RA and ZP; investigation, OP, RA, and ZP; resources, OP; data curation, RA and ZP; writing—original draft preparation, OP and RA; writing—review and editing, OP, RA, and ZP; visualization, ZP; supervision, OP; project administration, RA; funding acquisition, OP.

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CONFLICTS OF INTEREST

The authors declare no conflict of interest concerning the publication of this article. The authors also confirm that the data and the article are free of plagiarism.

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