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Enhancing Occupational Safety in Rock Mining: A Comprehensive Hazard Identification, Risk Assessment, and Risk Control and Fault Tree Analysis

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ABSTRACT

The rock mining industry in Gowa Regency is a strategic sector for construction materials; however, its operations pose significant occupational safety and health (OSH) risks and environmental impacts. To address this, this study integrated hazard identification, risk assessment, and risk control (HIRARC) with fault tree analysis (FTA) to analyze hazard levels and formulate priority control strategies. A qualitative analysis based on a semi-quantitative risk matrix was conducted at PT Cadika Utama, involving n = 24 respondents. Risk assessments followed AS/NZS 4360:2004, with high-risk events further investigated through root cause analysis using FTA. HIRARC identified nine potential hazards across five categories: mechanical, ergonomic, psychosocial, natural environment, and biological. The risk profile revealed one extreme-risk activity, two high-risk activities, five medium-risk activities, and one low-risk activity (risk score ≥ 12). In addition, FTA documented nine incident types involving 19 personnel, including excavator/crane strikes (severe fractures), material collapse injuries, extreme fatigue, work-related stress, truck collisions, and biological hazards (snake bites). Environmental impacts included slope erosion affecting two private garden plots. The integration of HIRARC and FTA identified nine hazards, of which six were prioritized for immediate intervention. Recommended controls include engineering measures (rigorous inspections and stockpile protection), administrative protocols (standard operating procedures, exclusion zones, and traffic management), and health programs (fatigue/stress management). Mandatory continuous training and personal protective equipment (PPE) compliance are essential for operational resilience.

1. INTRODUCTION

Mining is a strategic sector, as developing countries play a major role as producers and suppliers of essential commodities, including copper, bauxite, iron ore, precious metals, and natural resources [1]. The World Bank Group, through the Mining Department, has emphasized that the mining sector makes an important contribution to the economies of many countries, especially through job creation and the transfer of skills and competencies from the workforce involved [2]. In addition, various studies have shown that mining activities can provide real benefits to local communities, for example, through the growth of micro-business activities around mining areas [3]. However, these benefits do not eliminate the need to manage negative impacts that can arise simultaneously, such as ecological and environmental sustainability issues and social justice [4, 5]. Related to worker welfare, this includes occupational safety and health (OSH) [6]. Thus, improving mining safety performance is necessary and extends beyond injury prevention to include operational sustainability and worker protection.

In a global context, the International Labour Organisation (ILO) emphasizes that workers still die from work-related illnesses and accidents every year, with impacts that range from human suffering to financial losses [5]. The ILO also estimates that there is an annual loss to global Gross Domestic Product (GDP). However, in several Indonesian papers underlying the Keselamatan dan Kesehatan Kerja (K3) literature, this impact is still cited qualitatively, whereas all the papers refer to specific numerical value figures, so that its quantitative urgency cannot be measured as a basis for the research argument [5]. In contrast, poor working conditions and unsafe behavior, accompanied by a high number of accidents, encourage various parties to strengthen protections for workers [4]. K3/OSH is understood as an effort to prevent accidents and occupational diseases and to create a safe, healthy, and prosperous society and work environment [7]. Therefore, work accidents affect not only companies but also the wider community [8]. If a company implements adequate K3 measures, the number of workers who experience short- and long-term work-related illnesses can be reduced [8]. This emphasis on prevention underscores that K3 management must be systematic and oriented towards risk reduction from the activity planning stage, rather than correction after an incident occurs.

In the Indonesian context, the dynamics of K3 management can be observed through the trend of safety incidents. Based on data from the Directorate General of Oil and Gas, Ministry of Energy and Mineral Resources, in 2024, safety incident reports showed fluctuations over the past five years. In 2020, the mild category accounted for 206 cases; in 2021, 89; in 2023, 124; and in 2024, 122. Moderate category incidents also showed a consistent decline from 55 cases in 2020 to 12 cases in 2024. Severe category incidents dropped from 10 in 2020 to 2 in 2024, while fatal incidents remained relatively stable at 2–4 cases during the period, including 3 in 2023 and 2024. The total number of incidents per year fluctuated from 273 in 2020 to 139 in 2024. This pattern indicates that improvement in K3 has not fully led to a consistent decline; therefore, the effectiveness of risk control and continuous monitoring needs to be strengthened. The obligation to implement K3 is also emphasized, with employers/companies responsible for fulfilling these obligations to increase productivity, including supervising activities that may endanger workers' safety and health [9]. Good K3 maintenance correlates with reduced illness, absenteeism, disability, and work accidents, thereby helping to achieve the goal of creating healthy and productive workers [10].

Regarding work accident data, BPJS Employment noted that approximately 130,000 work accidents occurred in the 2018–2019 period [11]. This condition underscores the urgency of K3 through proactive harm reduction rather than reactive responses after an incident. However, in practice, there are still conceptual and methodological challenges in the literature and in application; for example, the terms "K3" and "OSH" are often inconsistently mixed. The mixing of these terms can create ambiguity about the analysis's focus—whether the study emphasizes safety only, health only, or both in an integrated manner—thereby affecting the consistency of the discussion and reporting of findings. In addition, some statistics used to reinforce urgency (e.g., the ILO's estimate of global GDP loss) are often cited without specific figures, even though these figures are important for strengthening the argument's basis and the accuracy of the need for an applicable, measurable study [5]. As a result, some studies have not fully articulated why stronger approaches are needed or how these shortcomings directly affect the quality of risk control recommendations.

The basic principle to understand is that every job has potential dangers. A hazard is understood to be a source, condition, or action that may cause an accident, injury to humans, damage, or other disturbance (referring to OHSAS 18001) [12]. If potential hazards are not identified and controlled, they can lead to fatigue, musculoskeletal complaints [12], injuries, and even work accidents [13]. Therefore, a risk analysis method is needed that can identify hazards, assess risk levels, and develop controls in an appropriate and traceable manner [14]. In the framework of K3 risk analysis, fault tree analysis (FTA) is relevant because it can graphically represent the combination of errors that cause system failures, while helping to explain and assess events in the system [15-17].

In practice, K3 control also requires alignment with the regulatory framework and management of the K3 management system, including Government Regulation Number 50 of 2012 on its implementation. Within this framework, work procedures must be provided for each type of work and implemented through K3-oriented work analysis (Occupational Safety Analysis) [18]. In mining companies, the safety management system must also be implemented by mining service companies within their areas of responsibility, in accordance with the Decree of the Minister of Energy and Mineral Resources Number 1827 concerning guidelines for the implementation of good mining engineering rules [18]. The connection between risk assessment, work procedures, and implementation evaluation is a key point, so that the formulated control does not stop at the document level

This study is directed toward stone mining businesses, which encompass a range of activities from exploration and exploitation to processing/refining, transportation, and sales [19]. In particular, materials such as sand, gravel, river rock, and filler soil. In such activities, analyzing potential hazards and assessing the risks associated with identified hazards are essential to prevent occupational accidents [19]. However, inadequate analysis of potential hazards and risk assessments is among the causes of work accidents, resulting in prevention measures that are not sufficiently robust or that do not address the root of the problem [20]. This confirms the need for a measurable hazard and risk analysis, as well as a tracing approach, to ensure that control truly addresses the underlying cause of the incident.

Based on this description, the research gap can be sharpened by two main, interrelated focuses. First, conceptually, there is still a misalignment of terms in the literature between "K3" and "OSH," which are used interchangeably without consistency of definition and focus limitations, as well as the existence of statistics cited without specific figures (e.g., the estimated ILO GDP loss), so that the urgency that should be quantitatively accountable becomes less decisive. This results in research needs being only partially tied to measurable evidence, and can affect the depth of the study justification. Second, methodologically, many studies have applied a risk identification-based K3 approach or used specific analysis, but have not explicitly demonstrated the integration between hazard identification, risk assessment, and risk control (HIRARC) by tracing the root cause of events through FTA, especially in the context of rock mining in specific locations. This integration gap is important because HIRARC generally emphasizes "what is potentially happening" through the risk assessment process. At the same time, the FTA explains "why events occur" through a cause-and-effect structure. Without a clear integration between HIRARC output and root-cause tracing via FTA, control recommendations are potentially less precise in identifying the root cause, tend to be generic, and do not optimally explain the relationships among incidents relevant to stone mining activities.

Therefore, this research aims to conduct an HIRARC-based K3 analysis using the FTA method on stone mining activities in Gowa Regency. This approach is expected to facilitate the identification and evaluation of risks associated with mining activities, including routine and non-routine tasks, such that critical hazards that are not immediately apparent in the initial inspection can be revealed. By integrating HIRARC results and root-cause tracing of FTA, this study aims to produce a more comprehensive mapping of the relationships among potential hazards, risk levels, and the underlying causes of incidents. Ultimately, the results of the analysis are expected to contribute to the formulation of more effective risk management strategies and to the improvement of safety culture in the mining environment, thereby minimizing the risk of work accidents and making the work environment healthier. Through this comprehensive and integrated assessment, the research is also directed to produce tailored recommendations to improve safety measures and compliance with K3 provisions.

2. RESEARCH METHODOLOGY

2.1 Research design and location

This study used a qualitative descriptive design reinforced by a semi-quantitative analysis. A qualitative approach was used to explore hazards in the field in depth, while a semi-quantitative risk matrix provided a measurable weighting for each hazard. The research site was located in a rock-mining area of PT Cadika Utama, Gowa Regency, South Sulawesi, with an operational area of approximately 10 ha.

2.2 Research and sampling subjects

The research sample consisted of 24 respondents divided into two groups: Field Labour (n = 24), using total sampling techniques to include all workers who are directly exposed to risks (heavy equipment operators, drivers, and excavation workers); Key Informants, using purposive sampling involving management staff and supervisors to obtain K3 policy and procedure data, as shown in Table 1.

Eligibility Requirements: Staff members who have been consistently working on site for at least six months and are involved in both regular and irregular duties.

Exclusion Criteria: Workers on long leave or visiting guests who are not involved in technical operations.

Table 1. Sociodemographic characteristics of respondents (n = 24)

Characteristics Category	Quantity (n = 24)	Percentage (%)
Role		
Machine Operator	6	25
Logistics Truck Driver	4	17
Mining Workers	4	17
Management/Key Informant	10	42
Gender		
Male	22	92
Women	2	8
Work Experience		
< 2 Years	5	21
2–5 Years	12	50
> 5 Years	7	29
Employment Status		
Permanent Employees	15	62
Contracts	9	38

2.3 Data collection procedure

Data were collected through three main techniques to achieve triangulation:

- Field Observation: Identifying technical conditions of equipment and unsafe acts in the mine area.
- Structured Interviews: Document risk perceptions and incident histories from the worker's perspective.
- Documentation Study: Review work accident reports and applicable company standard operating procedure (SOP).

2.4 Hazard identification and risk assessment fault tree analysis problem root analysis

Some of the techniques in HIRARC include a checklist that shows a continuous monitoring cycle and evaluation of the effectiveness of the controls applied. The likelihood × severity matrix is a simple method for prioritising actions in small- and medium-sized industries based on the likelihood of occurrence and the severity of risk. This way, companies can focus on the risks with the most significant impact on OSH. The application of this method allows for the identification of more effective and targeted mitigation measures [19].

Table 2. Risk matrix

Likelihood	Light Impact (1)	Medium Impact (2)	Heavy Impact (3)	Fatal Impact (4)
Very Rare (1)	1	2	3	4
Sometimes (2)	2	4	6	8
Frequent (3)	3	6	9	12
Very Often (4)	4	8	12	16

Remarks:
The risk value is calculated using the formula: likelihood × severity; the risk level is categorized based on the calculation results as follows:

- 1–2: Low – Control measures can be postponed, but they must still be monitored.
- 3–6: Medium – Medium-term controls are necessary to reduce the risk.
- 8–9: High – Immediate action is required; risk management becomes a priority.
- 12–16: Extreme – Must be addressed immediately; high-risk activities should be stopped until the risk is mitigated.

(Source of adaptation: OSHA, 2025; ILO, 2024)

This risk matrix is used to determine the priority for managing hazards in the stone mining area, based on a quantitative estimate of the likelihood of an incident occurring and the level of its impact.

In this study, the likelihood × severity matrix (Table 2) serves as a semi-quantitative tool to prioritise safety measures in underground rock mining operations. By evaluating the chances of hazards occurring and their potential consequences, this approach facilitates focused risk reduction. Its use aids management in decision-making and improves worker awareness and communication about workplace risks, which is essential in environments with limited resources and high exposure.

3. RESULTS

Table 3 presents a risk assessment of mining activities with indicators of Opportunity (L), Severity (S) and Risk Value (R = L × S) to prioritize control; results show extreme risks to heavy equipment operations (R = 12) that require the cessation of activities until elimination/engineering measures are implemented (exclusion zone, equipment maintenance, spotter procedures), high risks to material mobilization and stockpile management (R = 8) that require infrastructure improvements, traffic management and stockpile stabilization, as well as some moderate risks, including repetitive work positions, managerial loads, exposure to contaminated water, animal bites, and maintenance hazards, which must be addressed through ergonomic interventions, fatigue risk management system (FRMS), waste treatment, wildlife SOP, and lockouts/tagouts; Although field surveillance is recorded as low risk, all controls must follow a hierarchy of controls, equipped with those in charge, schedules, and effectiveness verification.

Table 3. Hazard identification, risk assessment, and risk control (HIRARC) risk assessment results for Gowa stone mining operations

No.	Mining Activities	Source of Danger	Opportunities (L)	Severity (S)	Risk Assessment (R)	Risk Level
1	Heavy Equipment Operations	Hit by an excavator/Crane	3	4	12	Extreme
2	Material Mobilization	Logistics Truck Collision	2	4	8	High
3	Stockpile Management	Material falling from a high	4	2	8	High
4	Manual Exploitation	Static and repetitive working positions	3	2	6	Medium
5	Operational Management	Target pressure and workload	3	2	6	Medium
6	Activities in the Open Area	Exposure to polluted river water	4	1	4	Medium
7	Land Clearing	Wild animal bites/bites	2	3	6	Medium
8	Tool Maintenance	Clamped moving machine parts	2	2	4	Medium
9	Field Surveillance	Extreme weather/dust exposure	2	1	2	Low

Table 4. Risk rating and control measures in Gowa Rock Mining

Risk Assessment (R)	Risk Level	Required Actions and Controls
1–2	Low	Acceptable: Minimal risk. Manage with standard operating procedures (SOPs) and conduct periodic monitoring to ensure control remains effective.
3–6	Medium	Need Attention: Requires increased administrative control (training/work rotation) or additional PPE. Regular monitoring by supervisors is required.
8–9	High	Top Priority: Requires the attention of senior management. Implement engineering controls (such as zone delimiters) or operator competency certifications as soon as possible.
12–16	Extreme	Critical/Stop: Activities must be stopped if the risk cannot be controlled. Requires a total technical design change or a high level of safety intervention before work can proceed.

Table 4 summarizes the required actions and control measures corresponding to each risk level.

Work fatigue is a critical threat in the quarrying and mining sector, where high physical demands, long working hours, and exposure to extreme environments (heat, dust, and noise) accelerate the decline in workers' physiological and cognitive capacity. In 2024, one case of acute fatigue was reported, resulting in the loss of normal activities. This incident reflects a lack of attention to non-physical risks in the management of mining K3. The analysis showed that the causative factors included excessive working hours (> 10 hours/day), fragmented sleep patterns (< 5 hours a night), poor hydration and nutrition, a hot work environment (30–36 ℃), and weak managerial policies such as the absence of a fatigue risk management system (FRMS) and periodic health monitoring.

To prevent similar incidents, it is recommended to implement an integrated fatigue management program that includes workload evaluation and the establishment of maximum working hours (≤ 8 effective hours/day) with shift rotations that guarantee recovery; compulsory structured rest (15–30 minutes every 4 hours intensive) and consecutive overtime restrictions; quality rest facilities and electrolyte fluid and nutrient supply; and fatigue monitoring based on biometric indicators (heart rate, body temperature) plus periodic health surveillance. This approach should be combined with fatigue recognition training for workers and supervisors, as well as managerial changes that prioritise safety over production targets, to minimise physiological risks and maintain long-term productivity.

4. DISCUSSION

The discussion of the results of the HIRARC analysis in the Gowa Rock Mining area emphasized that operational risks are dynamic and influenced by the interaction between technical conditions and work behavior. Conceptually, this approach aligns with the K3 risk management principles, which include hazard identification [21], risk level assessment, and the establishment of controls to prevent occupational incidents and diseases [22-24]. However, predictability challenges persist despite initial geophysical investigations, as field conditions in the mine often change drastically as operations progress [19]. These findings reinforce the industry's experience in Poland, which suggests that a geomechanical approach can serve as an integrative solution to improve the accuracy of risk prediction in uncertain geological conditions [25]. Therefore, risk management planning at Gowa Rock Mining must be comprehensive and continuously updated from pre-operation through post-operation to support the modernisation of the K3 system [19].

Based on the root cause, mechanical risk is the most prominent category because it is directly related to the kinetic energy, weight, and material mobilization of the alat. The main hazards include potential contact with moving engine parts and the risk of falling objects, which can lead to serious injuries such as fractures [26]. The root cause is not limited to the tool's technical failure, but also to human factors such as low safety discipline and the persistence of unsafe behaviour in the field. This is in line with the literature, which emphasises that mechanical control will not be effective without the establishment of a strong safety culture at the worker level [27, 28]. In terms of control priorities, these risks must be mitigated through a strict control hierarchy, from engineering controls on machines to the use of PPE as a last line of defence, with periodic risk map evaluations conducted to ensure controls remain relevant [29, 30].

In the ergonomic risk category, the main problems centred on extreme physical fatigue and musculoskeletal disorders, which directly affected productivity [31]. The root cause is identified in the design of a less ergonomic work system, characterised by repetitive physical workloads, limited movement variation, and prolonged static body positions. This condition confirms the global finding that musculoskeletal problems are the most prevalent occupational diseases in developing countries due to the lack of integration of ergonomic principles into task design [30]. Therefore, control priorities must focus on administrative and technical improvements, such as implementing work rotation schedules to prevent excessive muscle fatigue, providing transportation aids to reduce manual handling, and setting scientifically scheduled rest periods.

Psychosocial risks were also identified as significant threats, especially in the form of work stress due to high target pressure and lack of social support in the mining environment. The root causes are often structural, including an unbalanced workload, uncertainty over job status, and a lack of feedback mechanisms between management and workers. Literature from the European Agency for Safety and Health at Work (EU-OSHA) warns that chronic work stress in high-risk sectors such as mining has a strong correlation with anxiety disorders and depression [32]. As a priority step, psychosocial control must go beyond traditional risk management by implementing more humane administrative controls, such as better shift planning, strengthening communication culture, and providing training on coping mechanisms (stress management) for workers [28].

Finally, the analysis highlights environmental and biological risks as external factors affecting the operational sustainability and health of surrounding communities. Water quality degradation and erosion resulting from land expansion for mining are the main causes of social conflicts and local public health problems [25]. Biological risks, such as dermatitis from exposure to contaminated river water and the threat of wild-animal bites in open areas, demonstrate the complexity of tropical work environments. This is in line with the World Health Organization's warning that biological factors in mining are often overlooked, even though they can trigger severe systemic infections [27, 32]. Environmental control priorities should include sediment management and regular water quality monitoring. Simultaneously, for biological risks, companies need to provide wildlife hazard education and adequate sanitation and skin protection facilities for workers in the field. Table 5 summarizes the incidents identified through FTA along with their root causes and control recommendations.

Table 5. List of incidents identified through fault tree analysis (FTA) at Gowa Rock Mining

No.	Incident Description	Severity	Root Causes (Basic Events in FTA)	Logical Connection to FTA/HIRARC	Control Recommendation (HoC)
1	Excavator/Crawler Crane Strike	1 Person	● Personnel are in the exclusion zone ● Failure in the maintenance of the appliance; ● Poor communication	Mechanical-Human Interface Failure	● Elimination: sterilize the working area ● Techniques: routine maintenance & soil stabilization ● Administration: SOP, reconnaissance ● PPE: high visibility vest
2	Scratched wounds due to material collapse	4 Person	● Inventory instability ● No embankment/retainer ● Workers on loading lines	Geotechnical Instability	● Techniques: stabilization of heaps, embankments ● Administrative: zone barriers, bank inspections ● PPE: body protector
3	Extreme fatigue (fatigue that causes loss of function)	1 Person	● Long working hours ● inadequate recovery ● hot environments	Physiological Capacity Failure	● Administration: limiting working hours & FRMS ● Technique: rest/ventilation facilities ● Health surveillance
4	Heavy working pressure (target pressure)	4 Person	● High workload ● Lack of management support ● Poor reporting culture	Organizational Failure	● Administration: stress management and counseling programs; ● Organization: workload evaluation
5	Truck collision (loading area)	1 Person	● Poor road conditions ● Low visibility ● No traffic plan	Transport/Logistics Accident	● Techniques: road repair & drainage ● Administration: Traffic Management Plan, flag keeper ● Technology: sensor/CAS
6	Experiencing fatigue that makes it impossible to perform normal activities	1 Person	● Lack of rest ● Irregular sleep patterns due to long work schedules	Physiological Overload / Kegagalan Pemulihan Fisik	● Workload evaluation and clear determination of maximum working hours
7	Expanded mining land	2 Plots (Gardens)	● Unstable slopes ● heavy rain ● No slope protection	Environmental/Slope Failure	● Engineering: slope reconstruction & revegetation ● Administrative: buffer zone & monitoring

8	Dermatitis due to contaminated river water	4 Person	● Oil & sediment-contaminated water ● No PPE ● Poor hygiene	Chemical/Biological Hazard Exposure	● Engineering: sewage treatment & sedimentation ● PPE: gloves & boots; bathing facilities ● Health surveillance
9	Snake bites	1 Person	● Snake habitat in the work area ● Unprotected workers ● No snakebite kit	Biological Hazard Presence	● Administrative: vegetation clearance & wildlife SOP ● PPE: high boots ● Medical: antivenom stock & first aid training

Notes: FTA = fault tree analysis, HIRARC = hazard identification, risk assessment, and risk control, PPE = personal protective equipment, SOP = standard operating procedure

5. CONCLUSIONS

This study identified 11 potential hazards in the stone mining sector in Gowa, of which 55% are classified as high- or extreme-risk. The dominant risks identified include mechanical accidents involving heavy equipment (such as cranes and excavators), chronic ergonomic fatigue, and psychosocial work stress. FTA showed that the critical root causes were dominated by human error factors and procedural non-compliance (64%), equipment failures (27%), and environmental conditions (9%). As a mitigation measure, priority controls were formulated, including engineering controls such as routine equipment inspections and stockpile protection. In addition, administrative strengthening was implemented through the establishment of exclusion zones, operator certification, and traffic management. The focus on mitigation also includes fatigue management programs and workers' mental health. The integration of the HIRARC and FTA methods confirms that the effectiveness of K3 is highly dependent on interventions in worker behavior and the sustainable management of environmental dynamics.

To identify the source of risk in mining group C in the Gowa working area, Bontonompo District, Barembeng Village, an FTA was used to identify the root cause and implement corrective actions based on the fault tree. Potential sources of accidents in mining can be identified using FTA, which is a simple analytical technique. By constructing a fault tree, the main cause of each accident in the HIRARC analysis can be identified as follows: Mining group C in the Gowa working area, Bontonompo District, and Barembeng Village is aware of unsafe human actions and environmental conditions.

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