



HIRARC-Based Occupational Health and Safety Risk Assessment of Sludge Oil Utilization as an Alternative Fuel in the Cement Industry

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Article Info:

Article history:

Received: April 24, 2026

Revised: June 19, 2026

Accepted: June 23, 2026

Keywords:

Alternative Fuels; Cement Industry;
HIRARC; Occupational Health and
Safety; Risk Assessment; Sludge Oil

Abstract

Background: Using sludge oil as an alternative fuel promotes circular economy practices by reducing waste and fossil fuel use, while requiring systematic evaluation and control of occupational health and safety (OHS) risks.

Objective: This study aims to evaluate OHS risks associated with sludge oil utilization as an alternative fuel in the cement industry using the *Hazard Identification, Risk Assessment, and Risk Control (HIRARC)* framework.

Methods: This quantitative study was conducted at PT Solusi Bangun Indonesia Tbk, Cilacap Plant, in February 2026. Data were collected through field observations, structured questionnaires, and company documents from 20 purposively selected respondents involved in sludge oil management. Risk levels were assessed using the HIRARC methodology.

Results: A total of 28 potential hazards were identified across five operational stages: waste reception, temporary storage, pre-treatment, kiln utilization, and waste handling and emissions control. The identified hazards were predominantly chemical and physical in nature. Risk assessment results indicated that 21 risks were classified as very high, 4 as high, and 3 as medium. The most critical risks included transportation accidents, fires in buffer vessels, equipment-related injuries, explosions, and fires in the kiln area. These elevated risk levels were driven by the interaction between the flammable properties of sludge oil, suboptimal equipment conditions, workplace environmental factors, and limitations in existing control measures. Current risk controls were largely administrative and reliant on personal protective equipment (PPE), with limited implementation of engineering controls and hazard elimination strategies.

Conclusion: Strengthening engineering and systemic controls is essential to ensure safe, effective, and sustainable sludge oil utilization in the cement industry.

To cite this article: Wulandari, I. S., Martono, D. N., & Agustina, H. (2026). HIRARC-based occupational health and safety risk assessment of sludge oil utilization as an alternative fuel in the cement industry. *Glosains: Jurnal Sains Global Indonesia*, 7(3), 931–943. <https://doi.org/10.59784/glosains.v7i3.759>

INTRODUCTION

Sustainable industrialization positions the cement industry as a strategic sector characterized by high energy consumption and significant greenhouse gas emissions (Ige et al., 2024; Luhar et al., 2026; Miller et al., 2021). The clinker production process, which occurs at kiln temperatures of approximately 1,450°C, requires substantial fuel input and generates considerable CO₂ emissions. Therefore, efforts to reduce emissions are essential, particularly through improvements in energy efficiency and the adoption of more environmentally friendly alternative fuels.

Sludge oil is a type of industrial waste with considerable potential for use as an alternative fuel due to its hydrocarbon content, which ranges from 30% to 80% Ramirez (2019), and its

calorific value of approximately 3,765 kcal/kg (Jerez et al., 2021). Although this value is slightly lower than that of coal (5,000–6,000 kcal/kg), it remains sufficiently high to support its application in co-processing systems (Jagaba et al., 2022; Tang et al., 2023). However, sludge oil also contains volatile compounds and heavy metals (Murungi & Sulaimon, 2022; Tang et al., 2023; Essang (2024), which may pose risks to occupational safety and environmental health if not properly managed (Rosli et al., 2024).

Previous studies have shown that the utilization of sludge oil in cement kilns can reduce CO₂ emissions by approximately 5–8% while maintaining clinker quality (Tsiliogiannis & Tsiliyiannis, 2020; Murungi & Sulaimon, 2022; Tang et al., 2023). Nevertheless, existing research has predominantly focused on waste characteristics, process efficiency, and environmental impacts. Comprehensive analyses of occupational health and safety (OHS) risks across the entire sludge oil management chain, from transportation and storage to pre-treatment, kiln utilization, and waste and emission handling, remain limited (Chandrappa & Das, 2024). This gap is critical, as risks arise not only during combustion but throughout all stages of handling and processing.

In this context, risk assessment using the Hazard Identification, Risk Assessment, and Risk Control (HIRARC) methodology is particularly relevant for systematically identifying hazards, evaluating risk levels, and determining appropriate control measures (Lagrega et al., 2001; Blackman, 2016; Ramirez et al., 2019). PT Solusi Bangun Indonesia, Tbk. plant Cilacap provides a pertinent case study, as it is located approximately 3 km from the Cilacap Refinery, one of the largest sources of sludge oil in Indonesia, contributing 53.11% of national production, and has implemented sludge oil utilization as an alternative fuel. This context highlights both the opportunity and the necessity to ensure that OHS risk management is conducted systematically and aligned with actual operational conditions.

Accordingly, this study aims to assess the level of OHS risk associated with sludge oil utilization as an alternative fuel in the cement industry using the HIRARC approach, with the objective of supporting more structured and measurable risk control strategies.

METHOD

This study was conducted at PT Solusi Bangun Indonesia, Tbk. plant Cilacap, in February 2026, and focused on assessing OHS risks associated with sludge oil utilization as an alternative fuel in the cement production process. A quantitative approach was employed to objectively evaluate risk levels based on numerical data (Creswell & Creswell, 2018). The scope of the study encompassed all stages of sludge oil management within the co-processing system, including waste reception, temporary storage, pre-treatment, kiln utilization, and waste and emission handling. The unit of analysis included personnel acting as both risk sources and risk recipients within the operational system.

The study utilized both primary and secondary data. Primary data was collected through field observations, structured questionnaires, and analysis of internal company documents. Observations were conducted to identify facility conditions, work activities, and potential hazards at each stage of the process. The questionnaire was designed to assess the severity and likelihood of each identified hazard. Prior to the main data collection, the instrument was tested for validity and reliability through a pilot study.

Validity was assessed using Pearson correlation to examine the relationship between questionnaire items, while reliability was evaluated using Cronbach's alpha coefficient to measure internal consistency. The instrument was considered acceptable if it met established statistical criteria (Cooper et al., 2014). Document analysis included operational procedures, safety reports, and technical specifications related to waste management systems. Secondary data was obtained from relevant regulations, technical standards, and scientific literature.

A total of 20 respondents were selected using purposive sampling with a stratified approach based on their roles within the risk system. The risk source group consisted of personnel from four co-processing units and three logistics units (hereinafter referred to as NATHABUMI). The risk recipient group included personnel from three technical units, two OHS officers, three Environment, Quality, and Sustainability (EQS) staff members, three production and kiln operators, and two process engineering personnel. Respondent selection was based on work experience, level of operational involvement, and understanding of potential hazards to ensure the reliability and relevance of the data collected (Creswell & Creswell, 2018; Sugiyono, 2022).

Risk analysis was conducted using the HIRARC methodology, referring to ISO 31000:2018, ISO 45001:2018, and the Regulation of the Minister of Manpower No. 5 of 2018 concerning Occupational Safety and Health in the Work Environment. HIRARC is widely applied in OHS risk management to systematically identify hazards, assess risk levels, and determine appropriate control measures (Ridley, 2008; Hopkin, 2018). The initial stage involved context setting to define the scope, system boundaries, and risk assessment criteria, considering both internal and external organizational conditions. Hazard identification was conducted across all stages of sludge oil management by classifying hazards into physical, chemical, biological, ergonomic, and psychological categories, in accordance with occupational environmental hazard classifications.

Subsequently, risk assessment was performed through risk analysis and evaluation. Risk analysis involved assessing severity and likelihood using a five-point Likert scale (Sugiyono, 2022). These values were processed into a Severity Index (SI), which was then converted into a Probability Index (P) and an Impact Index (I) based on a quantitative risk analysis approach (Majid & McCaffer, 1997). The level of risk was calculated using the following equation:

$$R = P \times I \dots\dots\dots (1)$$

where *R* represents the OHS risk level, *P* the probability index, and *I* the impact index.

The results of the risk assessment were classified into categories ranging from very low to very high and subsequently mapped to determine control priorities. Risks categorized as high and very high were designated as priorities for mitigation (ISO 31000:2018; ISO 45001:2018). Risk control measures were developed based on the hierarchy of controls, including elimination, substitution, engineering controls, administrative controls, and the use of personal protective equipment (PPE) (Ridley, 2008). Recommended controls were evaluated in terms of effectiveness, feasibility, and compliance with applicable regulations. Finally, the data was analyzed using a quantitative descriptive approach and presented in tables and risk matrices in the Results and Discussion section to facilitate interpretation and identification of dominant risks.

RESULTS AND DISCUSSION

Results

This study evaluates the level of OHS risk across all stages of sludge oil management within the co-processing system, from waste reception to residue and emission handling. Given the integrated nature of the system, potential hazards and associated risks do not occur in isolation but are distributed throughout the entire operational chain. The analysis is based on assessments provided by respondents with direct involvement and in-depth understanding of sludge oil management activities, ensuring that the findings accurately reflect actual operational conditions.

Hazard Identification

The hazard identification process identified 28 potential hazards across five stages of sludge oil management, with chemical and physical hazards predominating.

Table 1. Potential Hazards in Sludge Oil Management in the Cement Industry

No.	Work Stage	Job Description	Potential Hazards	Hazard Type
1.	Waste reception	a. Verifying waste documents, including manifests and transport permits;	1) Leakage or spillage of sludge oil during loading and unloading due to hose or valve failure	Physical, Chemical
			2) Inhalation exposure to hazardous vapors (e.g., H ₂ S and VOCs) during unloading operations	Chemical
		b. Conducting visual inspections and sampling for analysis of calorific value, moisture content, and heavy metal content;	3) Transportation accidents (e.g., spills, collisions) leading to fire and environmental contamination	Physical, Chemical
			4) Injuries due to non-ergonomic postures during manual handling of transfer equipment	Ergonomic

No.	Work Stage	Job Description	Potential Hazards	Hazard Type
		c. Weighing and recording waste prior to unloading through the receiving system and piping to the buffer vessel in accordance with safety procedures	5) Work-related stress due to time pressure and high workload	Psychological
2.	Temporary storage	a. Storing sludge oil in a corrosion-resistant buffer vessel equipped with level monitoring and overflow protection systems;	6) Fire due to the flammable nature of sludge oil in the presence of heat or sparks	Chemical
		b. Maintaining material stability through flow circulation;	7) Explosion due to accumulation of flammable gases in inadequately ventilated areas	Chemical
		c. Monitoring operating conditions (temperature, gas potential) to ensure safety and quality	8) Leakage from buffer vessels or containment systems causing soil or water contamination	Physical, Chemical
			9) Inhalation exposure to hazardous vapors during storage	Chemical
			10) Exposure to pathogenic microorganisms in high-moisture sludge oil	Biological
			11) Exposure to high temperatures and noise affecting worker health and comfort	Physical
			12) Fatigue due to shift work and monotonous working conditions	Psychological
3.	Pre-treatment	a. Homogenizing sludge oil using a double screw pump system without a separate treatment unit;	13) Spillage during transfer causing slip hazards and environmental contamination	Physical
		b. Limited addition of additives to improve flow properties and combustion performance	14) Exposure to chemical additives used to improve flow characteristics	Chemical
			15) Heat exposure from equipment or heated sludge oil during pumping	Physical
			16) Injuries from contact with moving parts (e.g., double screw pumps) without adequate guarding	Physical
			17) Musculoskeletal disorders due to non-ergonomic operational and maintenance activities	Ergonomic
4.	Kiln utilization	a. Injecting sludge oil into the calciner via pumping and piping systems with controlled flow rate and fuel ratio;	18) Overpressure in fuel pipelines causing leaks	Physical, Chemical
			19) Fire due to imbalance in fuel-air ratio during injection	Chemical
			20) Excessive heat exposure from kilns and transfer pipelines	Physical
		b. Continuous monitoring of pressure, flow rate, and combustion temperature	21) Exposure to combustion gases (e.g., NO _x , SO ₂ , CO) despite emission control systems	Chemical
			22) Work stress due to high responsibility in maintaining process stability and safety	Psychological
5.	Waste and emission handling	a. Managing combustion residues (ash) reused as clinker raw material;	23) Inhalation exposure to residual ash dust from dust collection systems	Chemical
		b. Controlling emissions using systems such as electrostatic precipitators or bag filters integrated with Continuous Emission Monitoring Systems (CEMS)	24) Environmental contamination due to improper handling of hazardous residues	Chemical
			25) Exposure to heavy metals (e.g., Pb, Cr, Cd) during ash handling	Chemical
			26) Noise exposure from equipment such as dust collectors and ventilation systems	Physical
			27) Microbial growth in moist residues under certain conditions	Biological

No.	Work Stage	Job Description	Potential Hazards	Hazard Type
			28) Mental burden due to production targets and emission control responsibilities	Psychological

(Source: Author, 2026)

The distribution of hazard types indicates a clear predominance of chemical hazards, followed by physical hazards. This predominance is closely associated with the characteristics of sludge oil as hazardous and toxic (B3) waste, which contains volatile hydrocarbon compounds as well as hazardous gases such as H₂S and volatile organic compounds (VOCs). These substances pose significant risks through inhalation, dermal exposure, and potential fire or explosion events. In contrast, physical hazards primarily arise from operational conditions, including high temperatures, pressurized systems, moving mechanical equipment, and elevated noise levels. These hazards are particularly evident in stages involving pumping systems, kiln operations, and emission control units. The coexistence and interaction of chemical and physical hazards indicate that the risks extend beyond conventional occupational safety concerns to broader aspects of process safety. This underscores the need for integrated risk management approaches that address both worker safety and process stability.

Risk Assessment and Distribution

The results of the risk assessment indicate that most identified risks fall within the very high-risk category (21 risks), followed by high-risk (4 risks) and medium-risk (3 risks) categories. This distribution highlights the critical nature of OHS risks associated with sludge oil utilization across the operational system.

Table 2. Risk Assessment of Sludge Oil Management in the Cement Industry

No	Work Stage	Potential Hazard	Probability (%)	P Level	Impact (%)	I Level	Risk Score (R = P×I)	Risk Category	Recommended Action
1.	Waste reception	1) Leakage/spillage during loading-unloading due to hose/valve failure	38.8	Likely	35.0	Minor	12	High	Risk reduction measures recommended
		2) Exposure to H ₂ S and VOCs during unloading	48.8	Likely	50.0	Moderate	9	Medium	Mitigation prioritized based on resource availability
		3) Transportation accidents causing fire/environmental damage	21.3	Occasional	11.3	Insignificant	20	Very High	Requires immediate risk mitigation
		4) Injuries due to non-ergonomic handling	16.3	Occasional	13.8	Minor	16	Very High	Requires immediate risk mitigation
		5) Work stress due to workload/time pressure	21.3	Occasional	28.8	Minor	16	Very High	Requires immediate risk mitigation

2.	Temporary storage	6)	Fire due to flammable sludge oil	20.0	Occasional	7.5	Insignificant	20	Very High	Requires immediate risk mitigation
		7)	Explosion due to gas accumulation	25.0	Occasional	23.8	Minor	16	Very High	Requires immediate risk mitigation
		8)	Leakage causing environmental contamination	37.5	Likely	26.3	Minor	12	High	Risk reduction measures recommended
		9)	Exposure to chemical vapors	46.3	Likely	47.5	Moderate	9	Medium	Mitigation prioritized based on resource availability
		10)	Exposure to pathogens	15.0	Occasional	6.3	Insignificant	20	Very High	Requires immediate risk mitigation
		11)	Heat and noise exposure	37.5	Likely	33.8	Minor	12	High	Risk reduction measures recommended
		12)	Fatigue due to shift work	36.3	Occasional	33.8	Minor	16	Very High	Requires immediate risk mitigation
3.	Pre-treatment	13)	Spillage causing slips and contamination	30.0	Occasional	23.8	Minor	16	Very High	Requires immediate risk mitigation
		14)	Exposure to additives	16.3	Occasional	11.3	Insignificant	20	Very High	Requires immediate risk mitigation
		15)	Heat exposure during pumping	15.0	Occasional	10.0	Insignificant	20	Very High	Requires immediate risk mitigation
		16)	Contact with moving equipment	20.0	Occasional	7.5	Insignificant	20	Very High	Requires immediate risk mitigation
		17)	Musculoskeletal disorders	21.3	Occasional	26.3	Minor	16	Very High	Requires immediate risk mitigation
4.	Kiln utilization	18)	Overpressure causing leaks	45.0	Likely	38.8	Moderate	9	Medium	Mitigation prioritized based on resource availability
		19)	Fire due to fuel-air imbalance	47.5	Likely	21.3	Minor	12	High	Risk reduction measures

								recommended		
	20)	Heat exposure from kiln/pipes	36.3	Occasional	26.3	Minor	16	Very High	Requires immediate risk mitigation	
	21)	Exposure to NOx, SO ₂ , CO	26.3	Occasional	12.5	Minor	16	Very High	Requires immediate risk mitigation	
	22)	Work stress (high responsibility)	23.8	Occasional	28.8	Minor	16	Very High	Requires immediate risk mitigation	
5.	Waste and emission handling	23)	Exposure to ash dust	27.5	Occasional	23.8	Minor	16	Very High	Requires immediate risk mitigation
		24)	Environmental contamination	12.5	Occasional	15.0	Minor	16	Very High	Requires immediate risk mitigation
		25)	Heavy metal exposure (Pb, Cr, Cd)	13.8	Occasional	6.3	Insignificant	20	Very High	Requires immediate risk mitigation
		26)	Noise exposure	12.5	Occasional	11.3	Insignificant	20	Very High	Requires immediate risk mitigation
		27)	Microbial growth	15.0	Occasional	12.5	Minor	16	Very High	Requires immediate risk mitigation
		28)	Psychological burden	30.0	Occasional	30.0	Minor	16	Very High	Requires immediate risk mitigation

(Source: Author, 2026)

The distribution of risks within the risk matrix indicates that most hazards are characterized by moderate to high probability combined with significant impact. This pattern suggests that risks are not isolated or rare events but occur repeatedly as part of routine operational activities. Consequently, the overall risk profile reflects a high-frequency risk environment, requiring continuous and systematic control rather than reactive, incident-based responses. As shown in Figure 1, most risks are concentrated in the high and very high categories.

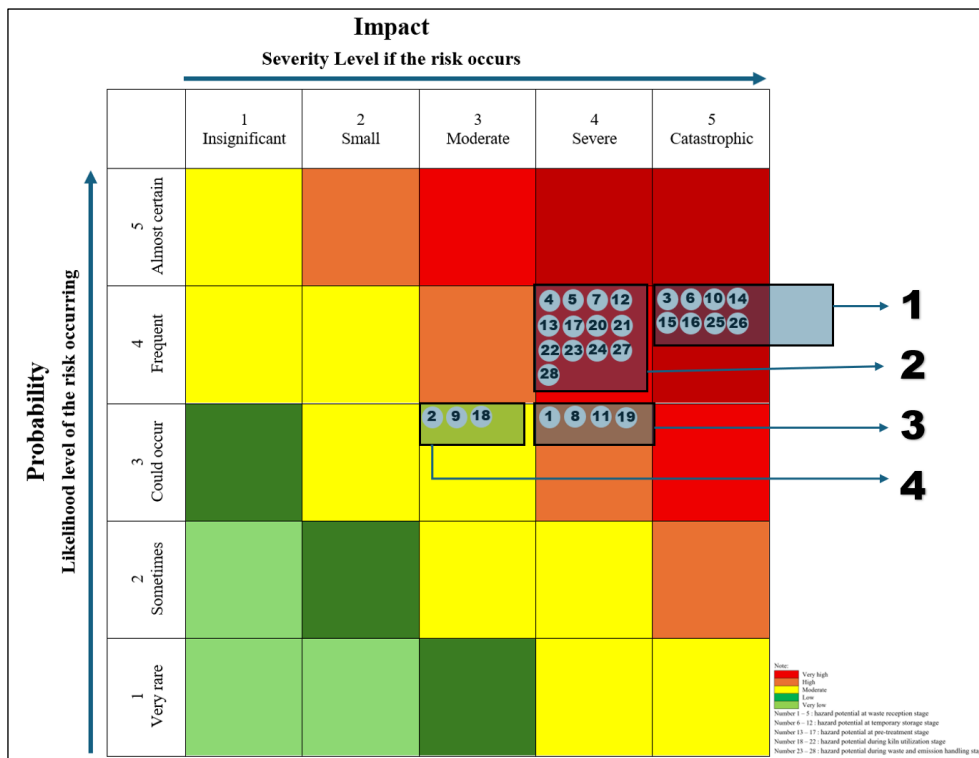


Figure 1. Risk Matrix of Sludge Oil Management in the Cement Industry (Source: Author, 2026)

The highest concentration of risks is observed in the pre-treatment stage and the waste and emission handling stage. These stages involve direct interaction between hazardous materials, thermal energy, and workers under dynamic operational conditions. The intensity of these interactions increases both the likelihood of system failure and the severity of potential consequences. These findings indicate that risk management efforts should not be limited to the combustion stage alone but must encompass the entire process chain, including upstream and downstream operations. A comprehensive approach is therefore essential to ensure effective mitigation of OHS risks.

The application of the Severity Index (SI) approach enables the quantification of respondents' perceptions of risk levels. However, these assessments should be interpreted with caution due to the potential for perceptual bias. Risk perception is often influenced by the frequency of experienced events, which may lead to the underestimation of low-probability but high-impact risks (Reason, 1997; Slovic, 2000).

Risk Priorities and Critical Characteristics

Priority risks are concentrated in activities involving material movement, energy accumulation, and direct human-system interactions. These activities represent critical points within the system due to intensive transfers of energy and hazardous materials.

The classification presented in Table 3 shows that risks in the critical category are predominantly associated with events that have the potential to cause fatalities and systemic escalation, such as transportation accidents, fires, and equipment failures. This aligns with the concept of process safety events, which emphasizes the control of high-energy scenarios with widespread consequences (Manuele, 2014). The distribution of risk priorities further indicates that high-consequence events do not necessarily correspond to high-probability events; however, they remain prioritized due to their severe impact. This highlights the importance of a consequence-based approach in risk prioritization and decision-making.

Table 3. Classification of Risk Criticality

Risk Priority	Risk Criticality (risk code)		
	Critical	Serious	Moderate
1	Transportation accidents (3); buffer vessel fires (6); injuries	Exposure to chemical additives (14);	Exposure to microorganisms (10); heat exposure (15)

	from mobile equipment (16)	metals (25); noise exposure (26)	
2	Buffer vessel explosion (7)	Exposure to combustion gases (21); dust exposure (23); noise exposure (26)	Ergonomic injuries (4); work stress (5); fatigue (12); operational spills (13); musculoskeletal disorders (17); kiln heat exposure (20); operational stress (22); environmental contamination (24); mental burden (28)
3	Kiln fire (19)	-	Sludge oil spills (1); containment leaks (8); temperature and noise exposure (11); microbial contamination (27)
4	System overpressure (18)	H ₂ S/VOC exposure (2); chemical vapor exposure (9)	-

(Source: Author, 2026)

System Failure Mechanism

The analysis presented in Table 4 indicates that risk events arise from interactions between active failures and latent conditions. Active failures are associated with human actions under operational conditions, while latent conditions originate from system design, organizational structures, and managerial weaknesses. The dominance of deficiencies in technical and engineering controls suggests that the system lacks adequate defensive layers to prevent risk escalation. Limitations in detection systems, ventilation design, and equipment safety features allow failures to propagate rather than being contained at an early stage. This confirms that safety improvements cannot rely solely on behavioral interventions but must also address systemic and structural weaknesses (Reason, 1997).

Table 4. Risk Analysis Based on the Swiss Cheese Model

Components	Risk Type (risk code)		
	Transportation Accidents (3)	Buffer Vessel Fire (6)	Equipment Injury (16)
Hazard Event	Transport accidents with potential for spills, fire, and fatalities	Fire due to sludge oil contact with ignition sources	Severe injuries from moving mechanical parts
Active Failure	Driver error, fatigue, procedural violations	Presence of uncontrolled ignition sources	Unsafe operator proximity and procedural non-compliance
Latent Conditions	Weak transport management system; limited fatigue management; inadequate working hours control	Inadequate gas detection and ventilation systems; weak hazardous area classification	Poor machine guarding; insufficient safety engineering design
Layer of Defense	Inconsistent SOP implementation and weak supervision	Ventilation is insufficient to prevent vapor accumulation	Dependence on operator behavior; limited engineering protection
Key Findings	Combined human and organizational failures in transport system	Predominant failure in engineering controls	Failure in human-machine interface and equipment design
Control Implications	Strengthen transport safety management and fatigue control	Improve gas detection systems and implement intrinsically safe design	Enhance machine guarding and safety engineering controls

(Source: Author, 2026)

Risk Control Evaluation

The evaluation presented in Table 5 and Figure 2 shows that risk control is predominantly reliant on administrative controls and PPE. These represent the final layers of defense and are highly dependent on worker compliance and behavioral consistency. The limited application of elimination and substitution indicates that hazard control has not been sufficiently addressed at the source level.

Table 5. Risk Control Based on the Hierarchy of Controls

Level of Control	Risk Type (risk code)		
	Transportation Accidents (3)	Buffer Vessel Fire (6)	Equipment Injury (16)
Elimination	Reduce transport distance through proximity-based sourcing	Minimize residence time of sludge oil to prevent vapor buildup	Eliminate manual interaction via automation or remote systems
Substitution	Closed-system tankers replacing open transport	Nitrogen blanketing (inerting system)	Intrinsically safe low-speed equipment
Engineering Controls	GPS tracking, speed limiter, safe routing, automatic braking	Gas detectors, fire suppression, ventilation, explosion-proof design	Machine guarding, interlocks, safety sensors, emergency stop systems
Administrative Controls	Fatigue management, defensive driving training, SOP enforcement	Permit-to-work systems, inspections, emergency response training	SOPs, safety training, monitoring, incident reporting
PPE	Helmets, seat belts, safety driving gear	Fire-resistant PPE	Gloves, face shields, protective clothing

(Source: Author, 2026)

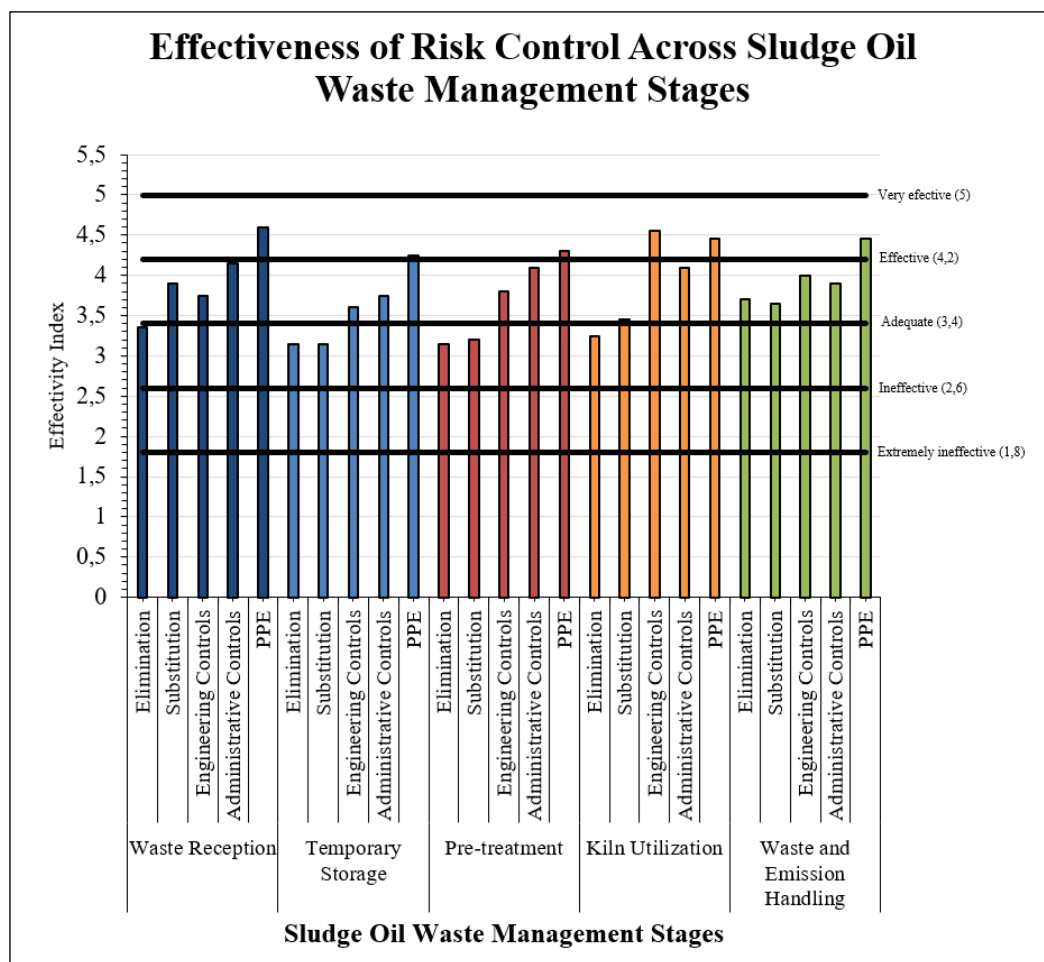


Figure 2. Effectiveness of Risk Control Across Sludge Oil Management Stages
(Source: Author, 2026)

Qualitative analysis indicates that control limitations are influenced by a combination of technical constraints, material characteristics, environmental conditions, and organizational factors. The interaction of these elements results in a control strategy that is predominantly mitigation-oriented rather than prevention-oriented, thereby explaining the gap between actual practices and the ideal hierarchy of control framework.

Discussion

The risk profile of sludge oil waste management in the cement industry is systemic in nature and characterized by recurring operational risks across all stages of the process. Rather than being isolated within specific activities, risks emerge from tightly coupled interactions among material properties, equipment conditions, and operational dynamics. Previous studies on sludge oil utilization have largely emphasized combustion efficiency, emission reduction, or waste characterization, with limited attention to how risks propagate across interconnected operational stages in co-processing systems. This study addresses this gap by revealing sludge oil risk as a continuous system-level phenomenon rather than a set of discrete occupational events.

The integrated analysis demonstrates a consistent linkage among risk distribution, priority classification, failure mechanisms, and control effectiveness. Risk mapping identifies structurally critical nodes within the system where hazard accumulation is most pronounced, while failure mechanism analysis shows that risk events are produced by interactions between active operational failures and latent system conditions. Control evaluation further indicates that existing mitigation measures are insufficient to interrupt escalation pathways. This alignment across analytical layers suggests that risk magnitude is not solely determined by hazard properties but is structurally reinforced by weaknesses in engineering design, system integration, and organizational controls.

This study contributes to the literature by integrating HIRARC with process safety logic and the Swiss Cheese Model across the full sludge oil utilization chain in cement co-processing systems. In contrast to prior research that predominantly focuses on environmental performance or process optimization, this study provides a system-level risk characterization spanning upstream logistics, intermediate processing, kiln operations, and downstream residue handling. The findings demonstrate that sludge oil-related risks propagate across stages through interconnected failure pathways, forming a continuous risk system rather than independent event clusters.

The identified risk characteristics are strongly aligned with process safety risk profiles, where low-frequency but high-consequence events dominate system vulnerability. However, current control practices remain heavily reliant on administrative measures and personal protective equipment (PPE). This mismatch reflects a structural imbalance in the risk control architecture, where higher-order preventive barriers such as engineering controls and hazard elimination are underdeveloped. As a result, risk reduction is primarily achieved through behavioral compliance rather than system robustness.

Overall, integrating HIRARC with quantitative risk assessment and qualitative system failure analysis provides a more comprehensive explanation of how hazards evolve into system-level risks. The findings suggest that effective risk reduction in sludge oil co-processing requires a shift from reactive, compliance-based safety management toward proactive engineering control and system design intervention. This transition is essential to ensure that circular economy strategies in cement production do not introduce unintended process safety vulnerabilities.

CONCLUSION

The application of the HIRARC methodology reveals that sludge oil management in the cement industry is characterized by a risk profile dominated by high and very high-risk categories across all operational stages. Chemical hazards predominate, and risk levels are driven by the combined effects of moderate-to-high probability events and significant impact severity. The most critical risks are associated with material handling activities, energy-intensive operations, and direct human-equipment interactions.

Failure mechanism analysis indicates that risk events arise from the interaction between active operational errors and latent deficiencies in technical and engineering systems. Limitations in detection systems, ventilation design, and equipment safeguarding reduce the effectiveness of existing controls and contribute to risk escalation. Furthermore, control evaluation shows a strong reliance on administrative controls and personal protective equipment (PPE), while source-level and engineering controls remain insufficient, resulting in suboptimal risk reduction.

This study has several limitations. The use of perception-based risk assessment introduces potential bias due to reliance on respondent experience rather than fully objective

operational data. In addition, the single-site case study design limits the generalizability of the findings across different industrial contexts. Future research should integrate real operational datasets and expand the scope to multiple cement industry configurations to develop a more robust and generalizable understanding of risk characteristics in waste-to-energy systems.

ACKNOWLEDGEMENT

The authors would like to acknowledge the Master's Program in Environmental Science, Universitas Indonesia, for its academic support in completing this study. This research was conducted without external funding and was fully supported by the authors. The authors also thank PT Solusi Bangun Indonesia, Tbk., plant Cilacap, particularly the CIL 2 unit, for granting access and facilitating data collection during the field study. Appreciation is extended to all operational personnel and respondents involved in sludge oil management for their cooperation, time, and valuable contributions to this research.

AUTHOR CONTRIBUTION STATEMENT

Intan Suci Wulandari contributed to the conceptualization of the study, data collection, data analysis, and manuscript drafting. Dwi Nowo Martono and Haruki Agustina contributed to supervision, methodological validation, and critical revision of the manuscript. All authors have read and approved the final version of the manuscript.

REFERENCES

- Blackman, W. C. (2016). *Basic hazardous waste management* (3rd ed.). Lewis Publisher. <https://doi.org/10.1201/9781420032604>
- Chandrappa, R., & Das, D. B. (2024). *Hazardous Waste BT - Solid Waste Management: Principles and Practice* (R. Chandrappa & D. B. Das (eds.); pp. 299–342). Springer International Publishing. https://doi.org/10.1007/978-3-031-50442-6_7
- Cooper, D., Bosnich, P. M., Grey, S. J., Purdy, G., Raymond, G. A., Walker, P. R., & Wood, M. J. (2014). *Project risk management guidelines: Managing risk with ISO 31000 and IEC 62198*. Wiley
- Creswell, J. W., & Creswell, J. D. (2018). *Research Design Qualitative, Quantitative, and Mixed Methods Approaches*. In *Sage Publications, Inc.* (5th ed., Issue 2).
- Essang, N. P., Olaye, M., & Zakariya, M. A. (2024). A Technical Review on Crude Oil Sludge: Current Trend of Treatment, Disposal, and the Way Forward.
- Hopkin, P. (2018). *Fundamentals of risk management: Understanding, evaluating and implementing effective risk management* (5th ed.). Kogan Page Publishers.
- Ige, O. E., Von Kallon, D. V., & Desai, D. (2024). Carbon emissions mitigation methods for cement industry using a systems dynamics model. *Clean Technologies and Environmental Policy*, 26(3), 579-597. <https://doi.org/10.1007/s10098-023-02683-0>
- Jagaba, A. H., Kutty, S. R. M., Lawal, I. M., Birniwa, A. H., Affam, A. C., Yaro, N. S. A., Usman, A. K., Umaru, I., Abubakar, S., Noor, A., Soja, U. B., & Yakubu, A. S. (2022). Circular economy potential and contributions of petroleum industry sludge utilization to environmental sustainability through engineered processes - A review. *Cleaner and Circular Bioeconomy*, 3(October). <https://doi.org/10.1016/j.clcb.2022.100029>
- Jerez, S., Ventura, M., Molina, R., Pariente, M. I., Martínez, F., & Melero, J. A. (2021). Comprehensive characterization of an oily sludge from a petrol refinery: A step forward for its valorization within the circular economy strategy. *Journal of Environmental Management*, 285, 112124. <https://doi.org/10.1016/j.jenvman.2021.112124>
- Lagrega, M. D., Buckingham, P. L., & Evans, J. C. (2001). *Hazardous Waste Management* (2nd Editio). McGraw-Hill.
- Luhar, S., Ashour, A., & Luhar, I. (2026). Decarbonising the Cement and Concrete Industry—A Step Forward to a Sustainable Future. *Journal of Composites Science*, 10(5), 226. <https://doi.org/10.3390/jcs10050226>
- Manuele, F. A. (2008). *Advanced safety management: Focusing on Z10 and serious injury prevention* (2nd ed.). John Wiley & Sons
- Miller, S. A., Habert, G., Myers, R. J., & Harvey, J. T. (2021). Achieving net zero greenhouse gas emissions in the cement industry via value chain mitigation strategies. *One Earth*, 4(10), 1398-1411. <https://doi.org/10.1016/j.oneear.2021.09.011>

- Murungi, P. I., & Sulaimon, A. A. (2022). Petroleum sludge treatment and disposal techniques: a review. *Environmental Science and Pollution Research*, 29(27), 40358–40372. <https://doi.org/10.1007/s11356-022-19614-z>
- Ramirez, D., Kowalczyk, R. M., & Collins, C. D. (2019). Characterisation of oil sludges from different sources before treatment: High-field nuclear magnetic resonance (NMR) in the determination of oil and water content. *Journal of Petroleum Science and Engineering*, 174(August 2018), 729–737. <https://doi.org/10.1016/j.petrol.2018.11.078>
- Reason, J. (1990). *Human error*. Cambridge University Press
- Ridley, J. (2008). *Health and safety in brief* (4th ed.). Routledge
- Rosli, N. A., Aziz, H. A., Pueh, L. L. L., Othman, I. B., Zawawi, M. H., & Hung, Y.-T. (2024). Management of Various Sources of Hazardous Waste BT - Waste Treatment in the Biotechnology, Agricultural and Food Industries: Volume 2. In L. K. Wang, M.-H. Sung Wang, & Y.-T. Hung (Eds.), *Handbook of Environmental Engineering* (2nd editio, pp. 19–64). Springer International Publishing. https://doi.org/10.1007/978-3-031-44768-6_2
- Slovic, P. (2000). *The Perception of Risk*. London: Earthscan Publications
- Sugiyono. (2022). *Metode penelitian*. Alfabeta.
- Tang, S. H., Lee, L. Z., Arsad, A., Zakaria, Z. Y., & Ahmad-Zaini, M. A. (2023). Unlocking the chemistry and properties of oil-containing sludge for potential utilization. *Ovidius University Annals of Chemistry*, 34(1), 28–33. <https://doi.org/10.2478/auoc-2023-0005>
- Tsiligiannis, A., & Tsiliyannis, C. (2020). Oil refinery sludge and renewable fuel blends as energy sources for the cement industry. *Renewable Energy*, 157, 55–70. <https://doi.org/10.1016/j.renene.2020.03.129>