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Risk Management Analysis and Mitigation Strategies for the Self-Heating Coal Phenomenon in Coal Loading Operations

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Abstract

The phenomenon of coal self-heating represents a critical risk during loading operations at Muara Jawa Port, as it can lead to temperature escalation, smoke generation, and potential fire hazards. This study examines the causes of coal self-heating, assesses its risk level, and evaluates the conformity of handling practices with the IMSBC Code and the IMDG Code. A descriptive qualitative approach was employed, involving direct observation aboard MV Golden Ace, temperature measurements using a thermal scanner, and risk analysis through Hazard Identification and Risk Assessment (HIRA). The findings indicate that coal temperatures reached 61°C, exceeding the safe threshold of 55°C as stipulated by the IMSBC Code, thereby necessitating the suspension of loading operations to allow for cooling. The HIRA results identify the highest risk phase occurring during the transfer of coal from barges to grab cranes, due to increased exposure to air and high humidity levels. While several operational procedures were found to be compliant with existing regulations, shortcomings remain in temperature documentation and gas monitoring practices. This study underscores the importance of early detection, continuous temperature surveillance, and effective mitigation strategies to enhance operational safety in coal loading activities.

Introduction

Coal is one of the strategic energy commodities that plays a vital role in Indonesia's maritime trade (Maulida & Prasetyo, 2026; Kusuma & Setiawan, 2026; Lee et al., 2026). East Kalimantan Province has emerged as a major hub for coal production and export, with Muara Jawa Port serving as a critical node for loading activities onto commercial vessels. At the same time, numerous studies have emphasized that coal is a cargo highly susceptible to spontaneous combustion or self-heating, a phenomenon driven by low-temperature oxidation processes that generate heat accumulation within the coal mass (Onifade & Genc, 2020). If this heat is not adequately dissipated, temperatures may rise progressively, leading to the formation of hot spots, smoke generation, and even large-scale fires during industrial operations or maritime transportation (Qiao et al., 2025; Goertz & Castriciones, 2026).

Recent studies indicate that the propensity for self-heating is influenced by the physico-chemical characteristics of coal such as moisture content, volatile matter, and sulfur content as well as by stockpile configuration and environmental conditions, including ambient temperature and humidity in tropical regions (Edy Nursanto et al., 2024; Zha et al., 2026; Chevalier et al., 2025). For instance, inadequate stockpile management under hot and humid climatic conditions has been shown to significantly increase the risk of spontaneous combustion during coal storage and transportation (Onifade. 2022; Sipilä et al., 2012; Onifade

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& Genc, 2020). These findings are consistent with recent comprehensive reviews on the current status and future prospects of coal spontaneous combustion research, which identify coal–oxygen interactions and heat accumulation as the key triggering mechanisms of self-heating within coal-based energy supply chains (Jin et al., 2025; Zhou et al., 2024; Li et al., 2025).

In the maritime context, coal self-heating is not merely a technical issue but also constitutes a significant threat to navigational safety (Yazar Okur & Gökbulut, 2026; Temel et al., 2024; Tuncel et al., 2023). Recent studies on the maritime transportation of coal indicate that self-heating onboard vessels may lead to cargo hold fires, environmental damage, and disruptions to shipping operations, thereby necessitating the development of risk assessment models specifically tailored to coal cargoes (Temel et al., 2024'; Huang et al., 2026; Guo et al., 2026). In Indonesia, cases of loading delays and coal cargo fires at the Muara Jawa anchorage area, as reported in the Indonesian Journal of Port and Shipping Management, demonstrate that this phenomenon is not merely a theoretical risk but has resulted in tangible operational consequences for vessels carrying coal in these waters (Suryadi et al., 2025).

Instances of self-heating have also been reflected in the operational experience of MV Golden Ace at Muara Jawa, where coal stored in barges exhibited rising temperatures accompanied by light smoke, forcing a temporary suspension of loading operations to allow for cooling measures. This situation highlights a gap between the hazards extensively documented in the literature and the practical implementation of risk management systems in the field. Conversely, the international regulatory framework has provided clear guidance on this matter. The International Maritime Solid Bulk Cargoes (IMSBC) Code classifies coal as a cargo susceptible to spontaneous heating and stipulates that coal must not be loaded if its temperature exceeds 55°C or if there is evidence of self-heating (International Maritime Organization, 2020). Similarly, the International Maritime Dangerous Goods (IMDG) Code underscores the importance of preventing heat accumulation and ensuring appropriate ventilation for cargoes prone to spontaneous combustion.

However, the effectiveness of such regulations is highly contingent upon their implementation at the operational level, including the accuracy of cargo declarations, consistency in temperature measurements prior to loading, continuous monitoring of hold atmospheres, and the readiness of ship crews to recognize early symptoms of self-heating. Recent studies emphasize the necessity of adopting systematic risk assessment approaches—such as Hazard Identification and Risk Assessment (HIRA) and fuzzy logic–based bow-tie models—to comprehensively map causal factors, event scenarios, and risk control barriers in coal transportation (Temel et al., 2024).

In light of this urgency, this study focuses on analyzing risk management and mitigation strategies for coal self-heating phenomena during loading operations at Muara Jawa Port, using the MV Golden Ace as a case study. Specifically, the research aims to identify the factors contributing to self-heating during the loading process, assess risk levels using the Hazard Identification and Risk Assessment (HIRA) method, evaluate the conformity of handling procedures with the IMSBC Code and the IMDG Code, and formulate practical and applicable risk management recommendations. It is expected that the findings will strengthen safety practices in bulk coal cargo operations and contribute to the development of operational policies at the ship, port, and regulatory levels.

Literature Review

Self-Heating in Coal

The phenomenon of self-heating in coal fundamentally constitutes a low-temperature oxidation process, in which coal slowly reacts with oxygen and generates internal heat. When

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the heat produced is not adequately dissipated into the surrounding environment, the temperature within the coal mass gradually increases, entering the incipient self-heating stage and potentially progressing to spontaneous combustion (Onifade & Genc, 2020). Existing studies emphasize that low-temperature coal oxidation involves oxygen consumption, the formation of gaseous and solid oxidation products, and is strongly influenced by coal properties, particle size distribution, and prior oxidation history.

More recently, Jin, Li, Liu, Yang, Cheng, Qi, Li, Hui, et al. (2025) reviewed the current status and future prospects of research on spontaneous coal combustion and demonstrated that self-heating represents a critical initial stage in the sequence of processes leading to fire, whether in mining operations, stockpiles, or transportation. These findings reinforce the view that understanding the characteristics of self-heating is essential not only during the mining phase but also throughout the logistics chain, including the transportation of coal as solid bulk cargo on seagoing vessels.

At the national level, a study entitled Analysis of the Effect of Temperature Increase in Coal indicates that coal stored in stockpiles with prolonged air exposure and extended storage periods has a high potential to experience gradual temperature increases due to oxidation. The longer the storage duration and the greater the volume of air within the stockpile, the greater the accumulation of heat. This evidence underscores that environmental and operational conditions in Indonesia significantly elevate the risk of coal self-heating (Yolanda et al., 2024).

Factors Contributing to Self-Heating in the Maritime Context

In the maritime context, self-heating is not solely determined by the physico-chemical properties of coal but is also strongly influenced by operational conditions along the logistics chain. Edy Nursanto et al. (2024) demonstrate that inadequate stockpile management such as excessive pile height, poor drainage, and insufficient spacing between piles significantly increases the risk of self-heating, particularly in hot and humid tropical climates such as Indonesia. Their study emphasizes that stockpile design and configuration play a direct role in controlling oxygen supply and heat dissipation within coal masses.

Local research by Kurniawan and Huda (2020) reinforces these findings by showing that coal quality, including moisture content and physical characteristics, together with storage and stacking practices, significantly affects the potential for self-combustion. Their analysis indicates that low-rank coal with certain moisture levels exhibits a higher propensity for self-heating when stored in compact piles over extended periods.

Furthermore, during loading operations, a study by Wahdiana and Achfan (2020) reports coal cargo temperatures exceeding 55 °C in barges prior to loading onto vessels. This finding underscores that improper handling and transfer of coal from stockpiles to barges or ships, without adequate temperature control and ventilation procedures, can trigger self-heating risks.

On the other hand, Zhou et al. (2024) developed numerical models of self-heating in coal stockpiles driven by natural convection, demonstrating that parameters such as porosity, pile height, and airflow velocity contribute to the formation of self-heating zones within coal masses. As coal is transferred from stockpiles to barges, then to grab cranes and ship holds, renewed exposure to air and changes in pile configuration may further accelerate oxidation processes. Accordingly, the combination of reactive coal characteristics and uncontrolled operational conditions at ports and onboard vessels constitutes a key trigger for self-heating in maritime coal transportation.

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Operational Impacts on Ports and Vessels

Self-heating of coal has direct implications for safety and operational performance at both ports and aboard vessels. At the port level, elevated coal temperatures may necessitate the suspension of loading activities, the implementation of cooling measures, deterioration in coal quality, and the incurrence of additional costs such as demurrage. A study by Restu Juniah et al. (2025), conducted in the context of mining operations and stockpile management, emphasizes that spontaneous coal combustion initiated by self-heating results in economic losses, operational disruptions, and occupational safety hazards, thereby underscoring the need for systematic management strategies.

Local research on coal at PIT 2 Banko Barat, PT Bukit Asam, indicates that self-heating can develop into spontaneous combustion when coal stockpiles receive sufficient oxygen supply and the generated heat cannot be effectively dissipated (Sarmidi et al., 2024). This condition is highly relevant to port loading activities, where coal is frequently transferred from stockpiles to barges and subsequently to grab cranes, processes that increase oxygen exposure and amplify the potential for temperature escalation. Similar findings are reported by Andryanto et al. (2025), who confirm a strong relationship between storage duration, internal temperature rise, and the likelihood of spontaneous combustion in one of PT Bukit Asam's stockpile areas. The study demonstrates that, in the absence of adequate early detection mechanisms, self-heating can progress rapidly and disrupt the coal distribution chain from mine to port.

From a maritime transport perspective, Temel et al. (2024), employing a Fuzzy Bow-Tie analysis to assess self-heating risks during coal transportation, show that failure to control triggering factors may lead to cargo hold fires, the release of toxic gases, and potential damage to the vessel. These findings are consistent with operational case reports indicating that coal with elevated temperatures combined with insufficient ventilation within cargo holds can generate hazardous concentrations of CO and CH_4. Consequently, self-heating affects not only the efficiency of loading and transportation operations but also vessel stability, crew safety, and compliance with international maritime safety regulations.

Early Detection and Monitoring

Early detection is an essential measure to prevent self-heating from developing into hazardous conditions. The 2020 edition of the IMSBC Code emphasizes the importance of measuring coal temperature prior to loading and throughout the voyage, and recommends the use of appropriate equipment to monitor hold temperatures and atmospheres, including the concentration of hazardous gases (International Maritime Organization, 2020). In practice, temperature measurement using thermal scanners while coal is still on barges or handled by grab cranes represents an initial method for assessing whether the cargo remains within safe limits before being loaded into the cargo holds.

Advancements in detection and monitoring technologies are also reflected in the study by Anghelescu and Diaconu (2024), which reviews a range of methods for monitoring coal self-heating and spontaneous combustion, including conventional temperature and gas sensors, remote sensing techniques, and data-driven modeling approaches to predict high-risk areas. Meanwhile, Li et al. (2022) demonstrate that variations in moisture content significantly influence the rate of oxidation and self-heating of coal under low-temperature conditions, underscoring the importance of monitoring environmental parameters such as humidity and temperature as integral components of a comprehensive monitoring system.

Findings from local studies further reinforce the necessity of multi-layered monitoring. The study by Muhamad Rizal Kautsar et al. (2025), entitled Monitoring Coal Temperature for the Prediction of Spontaneous Combustion at the North TAL RL Inpit Stockpile, reveals that

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although surface temperatures of the stockpile remained within a safe range (approximately ±28 °C), measurements taken at a depth of approximately 2 meters indicated temperatures reaching up to 100 °C, a level with a very high potential to trigger spontaneous combustion (Muhamad Rizal Kautsar et al., 2025). These results highlight that early detection cannot rely solely on surface temperature measurements, as internal heat accumulation may occur without visible indicators such as smoke or discoloration of the material.

Methods

This study is grounded in a descriptive qualitative approach, chosen to capture the complexity of the self heating phenomenon as it unfolds within real operational settings. Rather than reducing the phenomenon into isolated variables, this approach allows the researcher to engage directly with the dynamics of coal handling practices, environmental conditions, and human decision making processes that collectively shape risk emergence. The study is further positioned as an applied case study, focusing specifically on coal loading activities at Muara Jawa Port, with MV Golden Ace serving as the primary observational site. This focus enables a close examination of how risk is produced, perceived, and managed in situ, where theoretical knowledge and operational realities intersect.

The process of data collection was embedded within onboard practical training, which provided sustained and immersive access to the field. Through direct observation, the researcher followed the full sequence of coal handling operations, beginning from the transfer of coal from barges to grab cranes and continuing to the stage immediately before loading into the ship's cargo holds. This continuous engagement made it possible to observe not only routine procedures but also subtle variations in practice that may contribute to temperature escalation. In parallel, coal temperature measurements were conducted using a calibrated thermal scanner at multiple intervals during loading sessions. These measurements were intentionally taken at different operational moments in order to capture fluctuations that might otherwise remain unnoticed if observation were limited to a single time point.

The empirical basis of this study is built upon two interrelated forms of data. The first consists of primary data derived from direct temperature readings and visual assessment of the coal, including indications such as changes in coloration, the presence of smoke, and other signs associated with early stages of self heating. These observations were not treated as isolated indicators, but were interpreted in relation to the surrounding operational context. The second form of data comprises secondary sources, including international regulatory frameworks such as the IMSBC Code and IMDG Code, along with a body of scientific literature addressing coal self heating, spontaneous combustion, and risk management in maritime environments. Bringing these sources into dialogue with field observations allows the study to situate empirical findings within a broader framework of established knowledge and regulatory expectations.

The analytical process was carried out through a systematic effort to relate field based evidence to internationally recognized safety standards. Observed temperature patterns, handling procedures, and environmental conditions were examined in light of the thresholds and guidelines articulated in the regulatory frameworks. At the same time, a Hazard Identification and Risk Assessment approach was employed to structure the analysis of risk across different stages of the loading process. Each stage was carefully examined to identify potential hazards, trace their underlying causes, and evaluate their likelihood and severity. Through this process, risk is not treated as an abstract category, but as something that emerges from specific configurations of material conditions and operational practices. This allows for a more grounded understanding of where and how critical points of vulnerability arise.

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Results and Discussion

Overview of the Research Site

The research was conducted at Muara Jawa Port, a coal export port characterized by a tropical climate, relatively high humidity, and generally warm ambient temperatures. The logistics system involves the transfer of coal from barges to vessels using grab cranes, with temporary storage on barges prior to loading into the ship's cargo holds. The combination of tropical climatic conditions, elevated humidity levels, and potentially limited ventilation in the transfer areas creates an environment that is highly susceptible to self-heating phenomena. This observation is consistent with existing literature, which emphasizes that environmental conditions and the structural characteristics of coal stockpiles play a critical role in the risk of self-heating and spontaneous combustion (Jin et al., 2025).

Considering the inherent properties of coal and the loading process, including exposure to air during transfer operations and waiting times before loading into the cargo holds, the site presents conditions conducive to the occurrence of self-heating if mitigation and monitoring measures are not optimally implemented. These findings underscore the urgency of conducting risk management research at the loading stage, rather than focusing solely on the storage (stockpile) stage as has been predominantly addressed in prior studies.

Coal Temperature Measurement Results

During monitoring on board MV Golden Ace, the data indicate that coal temperatures during transfer operations (barge → grab crane → prior to loading into the cargo hold) ranged between 48 and 61 °C. The peak temperature was recorded during one loading session, reaching 61 °C, which exceeds the 55 °C threshold commonly regarded as the safe limit under international guidelines, such as those stipulated in the IMSBC Code. Consequently, loading operations were temporarily suspended to allow for cooling before the cargo was placed into the hold.

This temperature increase provides empirical evidence that the phenomenon of coal self-heating is not merely theoretical but occurs under real operational conditions. In particular, exposure to air and high humidity renders coal susceptible to reaching hazardous temperatures. Recent literature supports this finding, as studies on self-heating in coal stockpiles demonstrate that internal heat accumulation can escalate rapidly when ventilation and heat dissipation are inadequate (Thabari et al., 2023a).

Accordingly, these measurement results reinforce the hypothesis that coal transfer and handling within the maritime logistics chain require serious attention to temperature control and oxidative conditions, not only during storage but also throughout loading operations.

Self-Heating Risk Analysis (HIRA)

Based on temperature data and operational conditions, the risk analysis was conducted using the HIRA (Hazard Identification, Risk Assessment, and Risk Control) method. The results indicate that the most critical risk stage occurs during the transfer from the barge to the grab crane, where coal is exposed to ambient air under high humidity conditions. In addition, the waiting time prior to loading into the ship's cargo hold allows for intensified oxidation processes. At this stage, both the likelihood and severity are classified as high, as undetected and uncontrolled conditions may lead to advanced self-heating, smoke generation, or fire incidents.

These findings are consistent with recent studies employing risk-based models in coal transportation. For instance, research applying the "Fuzzy Bow-Tie" model demonstrates that inadequate ventilation, misdeclaration of coal properties, and insufficient temperature and gas

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monitoring are major contributing factors to self-heating or fire incidents on board vessels (Temel et al., 2024).

This HIRA underscores that risk control measures cannot rely solely on initial inspections; instead, continuous control is required, particularly during handling and transfer phases. Clearly defined mitigation barriers such as cooling, adequate ventilation, continuous monitoring, and proper documentation are essential to effectively reduce and manage self-heating risks.

Evaluation of IMSBC Code Implementation and Operational Practices

By comparing field conditions with international guidelines, particularly the International Maritime Solid Bulk Cargoes (IMSBC) Code, the evaluation indicates that although efforts to apply prescribed procedures have been undertaken, their implementation remains suboptimal in two principal aspects. 1) Temperature monitoring and documentation. During several loading operations, pre-loading temperature records and documentation of thermal scanning results were not maintained consistently. This deficiency increases the risk that potential “hot spots” may escape early detection; 2) Hold atmosphere and gas monitoring. No dedicated gas monitoring or specialized ventilation systems were in place when coal was loaded into cargo holds. This is a critical shortcoming, as the literature demonstrates that coal self-heating is often accompanied by the release of gases, including hazardous gases, and that ventilation control and gas monitoring constitute essential components of coal cargo risk management.

Accordingly, while an adequate regulatory framework is already in place, its practical application requires substantial improvement particularly in documentation, reporting, monitoring, and the training of ship crews and port operators to ensure that early risk detection and response can be carried out in a systematic and consistent manner.

Operational Implications and Mitigation Strategies

Table 1. Temperature Measurement Data

Measurement Date	Measurement Time	Average Temperature (°C)	Visual Condition of the Cargo	Action Taken	Remarks
10 June 2025	08:00–17:00	48°C	Normal coloration, no smoke observed	Loading continued	Safe
11 June 2025	08:30–17:30	53°C	Slightly warm, no gas emission detected	Loading continued	Stable
12 June 2025	09:00–18:00	61°C	Following morning temperature inspection, cooling was conducted; however, combustion occurred in the barge cargo	Loading halted	Cooling applied
13 June 2025	08:00–17:00	49°C	Normal coloration restored	Loading resumed	Post-cooling
14 June 2025	08:00–12:00	47°C	Stable condition	Loading completed	Safe

Table 2. Temperature Measurement and Risk Assessment Data

Activity Stage	Potential Hazard	Cause	Likelihood (L)	Severity (S)	Risk Level (R = L × S)	Risk Category	Control Measures

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Stockpile Storage	Coal heating due to oxidation	Excessive piling height, high moisture content	4	4	16	High	FIFO system, routine water spraying
Transfer from Barge to Grab	Self-heating triggered by air exposure	High moisture, oxidation reactions	4	5	20	High	Cooling measures, temperature inspections
Transfer to Ship's Hold	Formation of CO and CH_4 gases	Inadequate ventilation	3	5	15	Medium–High	Ventilation and gas monitoring
Hold Closure	Continued heating in a confined space	Lack of temperature monitoring	3	4	12	Medium	In-hold temperature control
Voyage	Fire inside the cargo hold	Presence of flammable gases	2	5	10	Medium	Inert gas system and CO monitoring

Based on the findings and analysis, several important operational implications can be identified. 1) First, vessel operators and port authorities must strengthen coal temperature inspection procedures prior to loading, not as a one-time activity, but during every transfer session from barges to grab cranes; 2) Second, continuous monitoring systems are required throughout the loading process, including the monitoring of temperature and gas levels within cargo holds, as well as proper ventilation and systematic documentation. The literature supports the use of real-time monitoring and mitigation systems such as ventilation, cooling, and the isolation or quarantine of overheated cargo to effectively control the risk of self-heating (Thabari et al., 2023b); 3) Third, standard operating procedures (SOPs) should be enhanced, accompanied by comprehensive training programs for ship crews and port personnel to enable early detection of self-heating indicators and the effective implementation of mitigation measures, including suspension of loading operations, cooling, ventilation, and cargo isolation; 4) Fourth, corporate and port-level regulations and internal policies must be strengthened to ensure that mitigation measures are not applied on an ad hoc basis, but are instead institutionalized as an integral component of routine risk management practices.

Overall, this study demonstrates that without adequate risk management and mitigation, coal loading operations at tropical ports such as Muara Jawa carry a high potential for self-heating and fire incidents, risks that are not merely theoretical but have been empirically observed in practice.

Figure 1. Identification of the Highest Temperature

Source: Author's personal documentation

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Figure 2. Charge Cooling Process

Source: Author’s personal documentation

Figure 3. Occurrence of the Self-Heating Phenomenon

Source: Author’s personal documentation

The results of the study support and expand upon the recent research by showing that coal self heating is not only limited to the conditions of storage but is also actively enhanced when loading coal onto the ship. The temperature recorded at over 55-C is also a confirmation that low temperature oxidation is active when it is exposed to operations. This aids Jin et al. (2025) in their view that self heating is developed throughout the entire logistics chain, and not solely at the stockpile stage. The current work refines this argument by pointing out the transfer stage as a critical نقطة with increasing oxidation rate because of newly exposed oxygen and unstable handling environments.

The literature of recent years emphasizes environmental and operational amplification of this process. As demonstrated by Edy Nursanto et al. (2024), humid tropical conditions contribute to the risk of oxidation, but the existing results show that even controlled conditions in stockpiles may be disrupted during handling. This disputes Kurniawan and Huda (2020) who focus on coal quality as a determining factor. Rather, evidence here indicates that operational exposure may dominate intrinsic material stability especially in fragmented maritime loading sequences.

The results are also comparable to modeling. Zhou et al. (2024) show that airflow and porosity generate localized heating and Li et al. (2022) verify that moisture increases the kinetics of oxidation. These processes are the reason why the visually stable coal in this study attained hazardous temperatures. Meanwhile, Muhamad Rizal Kautsar et al. (2025) demonstrate that internal heat might go unnoticed by surface monitoring, which can also be observed in this

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case. Anghelescu and Diaconu (2024) thus suggest to monitor them both, and there is a gap in the existing practice, as gas and internal temperature monitoring is still not extensive.

The outcomes are similar to those of Temel et al. (2024), who demonstrate that transitional stages introduce compounded risk pathways. The results of HIRA prove that the risk is highest during transfer, which means that it is not enough to examine it statically. This is also supported by Thabari et al. (2023a) that show that self heating increases nonlinearly beyond critical thresholds, such that early intervention is critical. According to Thabari et al. (2023b), real time mitigation, which still has not been developed in the observed operations, is emphasized.

The operative implications are also echoed by the wider research. Suryadi et al. (2025) and Restu Juniah et al. (2025) reveal that self heating disrupts logistics and creates losses in the economy proving that this is a safety, as well as efficiency concern. At the same time, regulatory gaps in implementation are indicative of the issues that Wahdiana and Achfan (2020) bring up, where compliance is non-systematic but procedural. This disconnection is reflected in the inconsistencies in monitoring and documentation which were found in this study.

The results show the significance of environmental context. Yolanda et al. (2024) point out that the risk of the base is greater under tropical conditions, whereas Andryanto et al. (2025) and Sarmidi et al. (2024) indicate that the exposure duration and oxygen jointly determine the potential of combustion. The current paper contributes to the fact that even short term exposure during loading can result in a rapid escalation. This supplements the actual description of the oxidation processes provided by Onifade and Genc (2020) and applies it to practical working conditions.

In sum, this paper establishes that coal self heating is a phenomenon that is molded through an ongoing interaction of material properties, environmental factors, and operations. The key observation is the loading transfer stage being a نقطة of increased vulnerability, where surveillance and control should be enhanced to deteriorate into the hazardous conditions.

Conclusion

This study demonstrates that the phenomenon of self-heating during the coal loading process at Muara Jawa Port constitutes a tangible risk that may compromise the operational safety of both vessels and port facilities. Temperature measurements conducted during loading activities indicate that coal temperatures reached up to 61°C, exceeding the safe threshold of 55°C as recommended by the IMSBC Code. This condition necessitated the temporary suspension of loading operations to allow for cooling, thereby confirming that tropical environmental conditions, exposure to air during cargo transfer, and the inherent characteristics of the coal significantly contribute to temperature escalation. The HIRA analysis further identifies the most critical stage as the transfer of coal from barges to the grab crane, during which oxidation intensifies and the likelihood of hot spot formation increases. Meanwhile, the evaluation of compliance with the IMSBC and IMDG Codes reveals that although several safety procedures have been implemented, deficiencies remain in temperature recording, cargo hold gas monitoring, and routine documentation practices.

Based on these findings, several recommendations are proposed to enhance the safety of coal loading operations. First, a more systematic temperature inspection regime should be implemented at every cargo handling cycle, rather than being limited to the initial stage only. Second, ship and port operators are advised to install continuous gas and temperature monitoring systems in cargo holds to enable early detection of potential self-heating during and after loading. Third, the establishment of quarantine standard operating procedures (SOPs) for overheated coal prior to loading, along with enhanced training for crew members

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and port personnel, would strengthen response capabilities to early indicators of self-heating. Fourth, comprehensive documentation of temperature measurements and mitigation actions should be made a mandatory component of the loading process to ensure compliance with the IMSBC Code and facilitate safety audits. Through the implementation of these strategies, it is expected that the risk of self-heating can be minimized, enabling coal loading operations at Muara Jawa Port to be conducted in a safer, more efficient manner and in full alignment with international safety standards.

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