Analysis of the Effect of Total Sulfur on Coal Loss due to Spontaneous Combustion at Stockpile 1, Air Laya Mine, PT Bukit Asam Tbk.

OTP RG Yehezkiel[1], Maulana Yusuf[2*] Muhammad Rendana[3], Eddy Ibrahim[4], Syamsul Komar[5]
[1,2,4,5]Department of Mining Engineering, Universitas Sriwijaya, Indralaya, South Sumatera, Indonesia
[3]Graduate Program of Environmental Science, Graduate School Universitas Sriwijaya, Palembang, South Sumatera, Indonesia

Corresponding Author's e-mail : *maulanayusuf@ft.unsri.ac.id*

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Abstract : Coal is a strategic energy commodity in Indonesia, but spontaneous combustion at stockpiles often degrades coal quality and causes physical loss. Total sulfur content is believed to play a role in the exothermic oxidation process that triggers spontaneous combustion, yet studies directly linking total sulfur to coal loss remain limited. This study aims to analyze the influence of total sulfur content on coal loss caused by spontaneous combustion at Stockpile 1, Air Laya Mine, PT Bukit Asam Tbk. The research uses a descriptive quantitative method with a case study approach. Spontaneous combustion simulations were conducted on four coal types with different calorific values (4,200, 4,900, 5,300, and 7,100 kcal/kg) over 360 minutes, measuring temperature and mass every 30 minutes. Results show an inverse relationship between total sulfur content and mass loss percentage. Coal with the lowest sulfur content (0.12% adb) experienced the highest mass loss (90.12%), while coal with the highest sulfur content (1.05% adb) experienced the lowest mass loss (71.82%). Total moisture proved more dominant than total sulfur in controlling the rate of coal loss. These findings are important as a basis for developing more targeted spontaneous combustion mitigation strategies in the coal mining industry.

Keywords : Total Sulfur, Spontaneous Combustion, Coal Loss, Stockpile, Total Moisture

Abstrak : *Batubara merupakan komoditas energi strategis di Indonesia, tetapi pembakaran spontan pada stockpile sering menurunkan kualitas batubara dan menyebabkan kehilangan fisik. Kandungan sulfur total diyakini berperan dalam proses oksidasi eksotermik yang memicu pembakaran spontan, namun penelitian yang secara langsung menghubungkan sulfur total dengan kehilangan batubara masih terbatas. Penelitian ini bertujuan untuk menganalisis pengaruh kandungan sulfur total terhadap kehilangan batubara yang disebabkan oleh pembakaran spontan di Stockpile 1, Tambang Air Laya, PT Bukit Asam Tbk. Penelitian menggunakan metode kuantitatif deskriptif dengan pendekatan studi kasus. Simulasi pembakaran spontan dilakukan pada empat jenis batubara dengan nilai kalor berbeda (4.200, 4.900, 5.300, dan 7.100 kkal/kg) selama 360 menit, dengan pengukuran suhu dan massa setiap 30 menit. Hasil penelitian menunjukkan hubungan berbanding terbalik antara kandungan sulfur total dan persentase kehilangan massa. Batubara dengan kandungan sulfur terendah (0,12% adb) mengalami* *kehilangan massa tertinggi (90,12%), sedangkan batubara dengan kandungan sulfur tertinggi (1,05% adb) mengalami kehilangan massa terendah (71,82%). Kadar air total terbukti lebih dominan daripada sulfur total dalam mengendalikan laju kehilangan batubara. Temuan ini penting sebagai dasar untuk mengembangkan strategi mitigasi pembakaran spontan yang lebih terarah dalam industri pertambangan batubara.*

Kata kunci : *Sulfur Total, Pembakaran Spontan, Kehilangan Batubara, Stockpile, Kadar Air Total*

INTRODUCTION

Coal remains a strategic energy commodity for Indonesia. In South Sumatra, PT Bukit Asam operates as one of the country's main coal producers. Coal quality determines both operational efficiency and market value. Moisture content, ash content, calorific value, and total sulfur content all affect this quality (Novianti et al., 2024; Salempang et al., 2025). Poor quality control leads to extra costs, reduced coal value, and physical coal loss during handling, stockpiling, and loading. Stockpile storage often changes coal characteristics. Spontaneous combustion causes many of these changes. This phenomenon starts when coal undergoes spontaneous oxidation while stored in large volumes. The internal temperature rises until it reaches the ignition point, and fire follows (Wen et al., 2003; Xu et al., 2023). Spontaneous combustion at stockpiles does more than damage coal quality. It also creates major economic losses for mining companies. Recent studies have shown that factors such as moisture content and particle size significantly influence the spontaneous combustion characteristics of stockpiled coal (Wu et al., 2024), while large-scale storage facilities require systematic prevention strategies to mitigate these risks (Shan et al., 2026; Zhang & Sun, 2022).

Sulfur content plays a key role in this process. When sulfur content increases or shifts during storage, the risk of economic loss and quality reduction grows. Research indicates that different forms of sulfur, particularly organic sulfur, can affect methane gas emissions and heat release during spontaneous combustion (S. S. et al., 2024). Several studies have examined the link between total sulfur and coal quality indicators such as calorific value (Novianti et al., 2024). Few studies, however, measure how total sulfur directly affects coal loss at stockpiles. Most existing research treats sulfur and quality (GCV, ash) separately from physical loss, without connecting the two. Furthermore, direct investigations into the temperature dynamics and mass loss specifically at PT Bukit Asam's Stockpile 1 remain limited (Andryanto et al., 2025).

This gap motivates the present study, titled "Analysis of Total Sulfur Effect on Coal Loss Due to Spontaneous Combustion at Stockpile 1, Air Laya Mine, PT Bukit Asam Tbk." The study identifies the characteristics of total sulfur content in coal at Stockpile 1. It then analyzes how total sulfur affects the rate of coal loss during spontaneous combustion. Finally, it examines the factors that strengthen or weaken this relationship. The core hypothesis states that total sulfur content at Stockpile 1 affects coal loss in two ways: physical mass loss from burning and quality loss from reduced calorific value (Qin et al., 2014; Xu et al., 2023). This hypothesis will be tested using total sulfur data linked to spontaneous combustion records at the site. The analysis will factor in coal mass loss. The expected outcome is a clear picture of how total sulfur relates to coal loss from spontaneous combustion, information that can support prevention decisions in future stockpile management (Shan et al., 2026; Zhang & Sun, 2022).

METHOD

This study uses a descriptive quantitative design with a case study approach. The research takes place at Air Laya Mine, PT Bukit Asam Tbk, Tanjung Enim, South Sumatra. The study runs for six months, from October 2024 to March 2025. This location fits the research because Air Laya is a major coal mine with frequent spontaneous combustion events, and PT Bukit Asam provides full data access. The study does not use human respondents. It uses coal samples instead. Researchers collect samples from Stockpile 1 and group them into four types based on calorific value: 4,200 kcal, 4,900 kcal, 5,300 kcal, and 7,100 kcal. Each type gets five samples, giving 20 samples total. Every sample goes through sizing with a 1-inch mesh sieve to keep particle size uniform. This step controls for particle size as a variable, so any difference in results comes from coal type, not particle variation.

The main materials are coal samples and kerosene. Kerosene acts as a catalyst to trigger the artificial combustion. The equipment includes an infrared thermometer (Benetech GM900) for surface temperature, a stopwatch (Joyko SW-510) for timing, a camera (Samsung NX1000) for documentation, a digital scale for mass loss, a 1-inch mesh sieve, a notebook (HP EliteBook 630), and SPSS and Microsoft Office for data processing. The core tool is a modified steel drum (radius 290 mm, height 890 mm). The drum acts as a closed combustion chamber. It lets researchers control air supply and limit fire spread outside the test area. Its performance is tracked through temperature readings every 30 minutes over a 6-hour burn cycle, and mass measurements at the same interval, producing a full heating and mass-loss curve for each sample.

Data collection follows four steps: sample collection at Stockpile 1, sizing to 1-inch mesh, laboratory testing (proximate and ultimate analysis to measure moisture, ash, volatile matter, fixed carbon, and elements like sulfur, carbon, and hydrogen), and field measurement. Field measurement covers ambient temperature, coal surface temperature, and mass loss, recorded every 30 minutes for 6 hours per sample. Data analysis combines descriptive statistics (mean, median, standard deviation, frequency distribution) with simple linear regression to test the relationship between total sulfur and coal loss. The study also compares economic losses from spontaneous combustion against losses from other causes, such as equipment damage or operational disruption. All results are presented through tables, charts, and maps using Excel and SPSS.

RESULT AND DISCUSSION

Proximate and Ultimate Coal Analysis

Observation ran for 360 minutes. Surface temperature was recorded every 30 minutes with an infrared thermometer. The study tested four coal types with different calorific values: ±4,200 kcal, ±4,900 kcal, ±5,300 kcal, and ±7,100 kcal.

Table 1. Proximate and Ultimate Analysis of Coal with a Calorific Value of ±4,200 kcal

Sample	TM (%Ar)	IM (%Adb)	Ash (%Adb)	Ash (%Ar)	VM (%Adb)	VM (%Ar)	FC (%Adb)	FC (%Ar)	TS (%Adb)	TS (%Ar)	GCV (%Adb)	GCV (%Ar)
1	36,40	15,10	3,80	2,85	40,50	30,34	40,70	30,49	0,10	0,07	5.624	4.213
2	36,70	15,20	3,60	2,69	41,20	30,75	40,00	29,86	0,10	0,07	5.612	4.189
3	35,80	13,30	4,40	3,26	42,40	31,40	39,90	29,55	0,13	0,10	5.702	4.222
4	37,60	15,40	3,80	2,80	41,90	30,90	38,90	28,69	0,10	0,07	5.551	4.094
5	36,70	16,60	1,70	1,29	41,90	31,80	39,80	30,21	0,15	0,11	5.614	4.261
x	36,64	15,12	3,46	2,58	41,58	31,04	39,86	29,76	0,12	0,09	5.621	4.196

Table 2. Proximate and Ultimate Analysis of Coal with a Calorific Value of ±4,900 kcal

Sample	TM (%Ar)	IM (%Adb)	Ash (%Adb)	Ash (%Ar)	VM (%Adb)	VM (%Ar)	FC (%Adb)	FC (%Ar)	TS (%Adb)	TS (%Ar)	GCV (%Adb)	GCV (%Ar)
1	28,70	15,20	3,00	2,52	40,40	33,97	41,40	34,81	0,27	0,23	5.791	4.869
2	29,10	15,20	2,10	1,76	40,60	33,95	42,10	35,20	0,13	0,11	5.822	4.868

3	31,00	16,70	1,00	0,83	39,70	32,88	42,60	35,29	0,10	0,08	5.876	4.867
4	28,90	15,00	1,60	1,34	40,30	33,71	43,10	36,05	0,11	0,09	5.892	4.928
5	29,50	14,60	7,70	6,36	41,60	34,34	42,10	34,75	0,13	0,11	5.963	4.923
x	29,44	15,34	3,08	2,56	40,52	33,77	42,26	35,22	0,15	0,12	5.869	4.891

Table 3. Proximate and Ultimate Analysis of Coal with a Calorific Value of ±5,100 kcal

Sample	TM (%Ar)	IM (%Adb)	Ash (%Adb)	Ash (%Ar)	VM (%Adb)	VM (%Ar)	FC (%Adb)	FC (%Ar)	TS (%Adb)	TS (%Ar)	GCV (%Adb)	GCV (%Ar)
1	25,40	9,90	1,40	1,16	42,30	35,02	46,40	38,42	0,23	0,19	6.342	5.251
2	25,50	10,40	1,50	1,25	42,10	35,01	46,00	38,25	0,25	0,21	6.353	5.282
3	24,90	10,60	1,50	1,26	42,40	35,62	45,50	38,22	0,36	0,30	6.339	5.325
4	26,80	11,90	1,60	1,33	41,80	34,73	44,70	37,14	0,23	0,19	6.402	5.319
5	26,80	12,40	1,10	0,92	41,20	34,43	45,30	37,85	0,31	0,26	6.395	5.344
x	25,88	11,04	1,42	1,18	41,96	34,96	45,58	37,98	0,28	0,23	6.366	5.304

Table 4. Proximate and Ultimate Analysis of Coal with a Calorific Value of ±5,300 kcal

Sample	TM (%Ar)	IM (%Adb)	Ash (%Adb)	Ash (%Ar)	VM (%Adb)	VM (%Ar)	FC (%Adb)	FC (%Ar)	TS (%Adb)	TS (%Ar)	GCV (%Adb)	GCV (%Ar)
1	6,90	4,20	5,20	5,05	40,40	39,26	50,20	48,79	0,65	0,63	7.371	7.163
2	6,10	0,80	8,30	7,86	32,30	30,57	58,60	55,47	0,51	0,48	7.556	7.152
3	8,40	2,10	4,50	4,21	38,50	36,02	54,90	51,37	1,12	1,05	7.639	7.147
4	6,40	1,40	6,30	5,98	36,90	35,03	55,40	52,59	1,49	1,41	7.534	7.152
5	6,20	1,40	6,90	6,56	36,70	34,91	55,00	52,32	1,48	1,41	7.533	7.166
x	6,80	1,98	6,24	5,93	36,96	35,16	54,82	52,11	1,05	1,00	7.527	7.156

Tables 1 through 4 present the proximate and ultimate analysis results for each coal type. The data show a clear pattern. Low calorific coal (±4,200 kcal) has an average total moisture (TM) of 36.64%, volatile matter (VM) of 41.58% adb, and fixed carbon (FC) of 39.86% adb. High calorific coal (±7,100 kcal) has much lower TM, only 6.80%, VM of 36.96% adb, and the highest FC, 54.82% adb. This pattern matches coal rank classification theory. Higher rank coal holds less moisture and more fixed carbon. High moisture in low rank coal opens up the coal pores. Open pores speed up contact with oxygen. Fast oxygen contact triggers early spontaneous oxidation. High rank coal has a denser pore structure. This dense structure slows oxygen diffusion into the coal mass. This finding supports self-heating theory, which places moisture and volatile matter as key indicators of oxidation susceptibility.

Total Sulfur Content in Coal

Table 5 summarizes total sulfur (TS) content for the four coal types. TS rises as calorific value increases. Coal at ±4,200 kcal records the lowest and most uniform TS, averaging 0.12% adb. TS climbs gradually in coal at ±4,900 kcal (0.15% adb) and ±5,300 kcal (0.28% adb). TS peaks in coal at ±7,100 kcal, averaging 1.05% adb, with a wide spread across samples, from 0.51% to 1.49% adb.

Table 5. Total Sulfur Content Across Coal Types

Coal Type	TM (%Ar)	Ash (%Ar)	VM (%Ar)	FC (%Ar)	TS (%Ar)	GCV (%Ar)
±4.200 kkal	36,64	2,58	31,04	29,76	0,09	4.196
±4.900 kkal	29,44	2,56	33,77	35,22	0,12	4.891
±5.300 kkal	25,88	1,18	34,96	37,98	0,23	5.304
±7.100 kkal	6,80	5,93	35,16	52,11	1,00	7.156

This positive link between calorific value and sulfur content relates to the origin of coal mineral matter. Higher rank coal forms through a longer coalification process. This process allows greater accumulation of sulfide minerals, such as pyrite. The wide TS spread in high calorific coal points to uneven pyrite distribution within the coal seam. This is not unusual. Mineral matter distribution rarely stays uniform within a single seam, even within the same stockpile.

Effect of Total Sulfur Content on Coal Loss from Spontaneous Combustion

The spontaneous combustion simulation ran for 360 minutes across all four coal types. Mass was measured every 30 minutes. Table 6 summarizes maximum temperature and total mass loss percentage.

Table 6. Coal Mass Loss Percentage from Spontaneous Combustion

Coal Type	Average Max Temperature (°C)	Average Mass Lost (kg)	Mass Loss (%)
±4.200 kkal	684,07	9,01	90,12
±4.900 kkal	637,24	8,92	89,24
±5.300 kkal	665,37	8,64	86,42
±7.100 kkal	523,42	7,18	71,82

Table 6 shows an inverse relationship between TS content and mass loss percentage. Coal with the highest TS (±7,100 kcal) lost the least mass. Coal with the lowest TS (±4,200 kcal) lost the most mass. This finding contradicts the common assumption that sulfur drives spontaneous coal combustion. Sulfur, mainly in pyrite form, can trigger exothermic reactions through FeS2 oxidation. However, these results show that sulfur plays a secondary role at Stockpile 1, Air Laya Mine. Moisture and volatile matter appear more dominant in controlling the rate and scale of mass loss. Low calorific coal holds high moisture that evaporates fast under heat exposure. This fast evaporation opens the coal pore structure and speeds up organic carbon oxidation, regardless of its low sulfur content.

Factors That Strengthen and Weaken the Influence of Total Sulfur

Table 7. Percentage of Coal Loss Due to Spontaneous Combustion

Coal Type	Sample	Max Temperature (°C)	Loss Mass (kg) from 10 kg	Loosing Percentage (%)
±4.200 kkal	1	655,30	8,90	89,00
	2	658,86	8,98	89,80
	3	725,30	9,13	91,30
	4	687,71	9,07	90,70
	5	693,19	8,98	89,80

	x	684,07	9,01	90,12
±4.900 kkal	1	611,10	8,94	89,40
	2	677,44	8,90	89,00
	3	610,24	8,91	89,10
	4	676,15	8,99	89,90
	5	611,28	8,88	88,80
	x	637,24	8,92	89,24
±5.300 kkal	1	635,50	8,68	86,80
	2	700,15	8,50	85,00
	3	649,47	8,73	87,30
	4	684,60	8,68	86,80
	5	657,12	8,62	86,20
	x	665,37	8,64	86,42
±7.100 kkal	1	512,20	7,12	71,20
	2	503,49	7,21	72,10
	3	547,57	7,25	72,50
	4	509,62	7,19	71,90
	5	544,22	7,14	71,40
	x	523,42	7,18	71,82

Table 7 present the temperature and duration relationship for each TS group. Coal at ±4,200 kcal shows the fastest and highest temperature spike, reaching 725°C at minute 90. Coal at ±4,900 kcal peaks at 677°C at minute 120. Coal at ±5,300 kcal rises more slowly, peaking at 700°C at minute 120. Coal at ±7,100 kcal rises the slowest and lowest, peaking at only 544°C. In low calorific coal (±4,200 kcal), high moisture content (36.64%) weakens sulfur's influence on spontaneous combustion. Fast water evaporation opens the coal pores. Open pores speed up carbon oxidation with air. This coal burns out from carbon oxidation before its low sulfur content, 0.12%, can have a meaningful effect.

In high calorific coal (±7,100 kcal), low moisture content (6.80%) makes the coal more stable and resistant to sudden combustion. However, high sulfur content, 1.05% adb, plays a major role once the coal slowly heats up to 523.42°C. At this temperature, sulfur oxidation starts to degrade coal chemical quality and release harmful SO2 gas into the environment. This finding matters for coal stockpile management. Spontaneous combustion control cannot focus on sulfur content alone. Moisture and volatile matter deserve equal attention, especially for low rank coal. For high rank coal, sulfur monitoring stays important because of its role in degrading coal chemical quality and generating SO2 emissions, even though its physical mass loss risk is lower.

Discussion

The findings from the proximate and ultimate analyses reveal a systematic relationship between coal rank and quality parameters, a pattern that aligns well with established coalification theory. As calorific value increases from ±4,200 kcal/kg to ±7,100 kcal/kg, there is a marked decrease in total moisture from 36.64% to 6.80% ar and a corresponding increase in fixed carbon from 29.76% to 52.11% ar. This progression is consistent with the understanding that higher-rank coals possess denser, less porous structures due to more advanced metamorphism (Salempang et al., 2025; Xu et al., 2023). The data also demonstrate an increase in total sulfur content alongside rank, peaking at 1.05% adb in the highest calorific coal. This positive correlation is attributable to the prolonged coalification process, which facilitates the accumulation of sulfide minerals, particularly pyrite, although its distribution within a seam can be uneven (Novianti et al., 2024; Salempang et al., 2025). The experimental results demonstrate an inverse relationship between total sulfur content and mass loss percentage, a finding that contradicts the common assumption that sulfur is a primary driver of spontaneous combustion. The low-sulfur, low-rank coal at ±4,200 kcal experienced the greatest mass loss at 90.12%, while the high-sulfur, high-rank coal at ±7,100 kcal lost the least mass at 71.82%. This counterintuitive result suggests that although pyrite oxidation is exothermic and can trigger self-heating (Qin et al., 2014; Wen et al., 2003), sulfur plays a secondary role at Stockpile 1, Air Laya Mine, PT Bukit Asam Tbk., where moisture and volatile matter appear more dominant in controlling the rate and scale of mass loss.

The high moisture content in low-rank coal emerges as the dominant factor driving mass loss, as rapid evaporation under heat exposure opens the coal pore structure and accelerates the oxidation of organic carbon, regardless of the low sulfur content (Wu et al., 2024). This observation is consistent with the findings of Andryanto et al. (2025), who conducted research at the same location and confirmed that low-rank coal with the lowest calorific value exhibited the fastest and highest temperature spike, reaching 725°C, while high-rank coal only reached 544°C. The mechanism of rapid water evaporation explains why the ±4,200 kcal coal achieved its peak temperature in only 90 minutes, as the volumetric shrinkage and pore opening dramatically enhance oxygen diffusion into the coal matrix. Wu et al. (2024) further demonstrated that moisture and particle size significantly influence the four-stage heating process during spontaneous combustion, where stage II is characterized by significant moisture evaporation that produces a low and fluctuating heating rate. This evidence reinforces the argument that for low-rank coals with moisture levels exceeding 35%, the physical loss of mass due to carbon oxidation proceeds so rapidly that the low sulfur content, typically below 0.15% adb, cannot exert a meaningful influence on the combustion process. In contrast, high-rank coal at ±7,100 kcal possesses a denser pore structure due to its low moisture content (6.80% ar), which slows oxygen diffusion into the coal mass and makes it more stable and resistant to sudden combustion (Salempang et al., 2025). However, at the elevated temperature of 523.42°C, the high sulfur content of 1.05% adb begins to play a significant role through sulfur oxidation, which degrades coal chemical quality and releases harmful sulfur dioxide gas into the environment (S. S. et al., 2024; Xu et al., 2023).

The role of sulfur in spontaneous combustion has been extensively studied, yet the mechanisms remain complex and context-dependent. The oxidation of pyrite (FeS_2) proceeds through a series of exothermic reactions that can release significant heat, as documented by Wang et al. (2021), who identified the following sequence: $2FeS_2 + 2H_2O + 7O_2 \rightarrow 2FeSO_4 + 2H_2SO_4 + Q_1$, followed by $12FeSO_4 + 6H_2O + 3O_2 \rightarrow 4Fe_2(SO_4)_3 + 4Fe(OH)_3 + Q_2$, and $FeS_2 + Fe_2(SO_4)_3 + 3O_2 + 2H_2O \rightarrow 3FeSO_4 + 2H_2SO_4 + Q_3$. These reactions release thermal energy that can drive spontaneous combustion when heat dissipation is hindered. However, the present study found that at sulfur concentrations below 2%, which is the threshold identified by Bhattacharyya (1971) as necessary for significant pyrite-driven self-heating, other factors become more dominant. The maximum total sulfur content recorded in this study was only 1.05% adb, well below this threshold, which explains why sulfur's contribution to physical mass loss was overshadowed by moisture and volatile matter. Furthermore, Wang et al. (2021) noted that colloidal $Fe(OH)_3$ produced during pyrite oxidation can block coal pore structures and slow the oxidation reaction, creating an inhibitory effect alongside the heating effect. This dual nature of sulfur's influence complicates the prediction of spontaneous combustion risk based solely on total sulfur content.

The relationship between sulfur content and calorific value observed in this study, where sulfur increases from 0.12% adb in the lowest rank coal to 1.05% adb in the highest rank coal, reflects the geochemical history of coal formation. Higher-rank coals undergo more extensive coalification, which allows for greater accumulation of sulfide minerals, although the distribution of these minerals within a single seam is rarely uniform (Novianti et al., 2024; Salempang et al., 2025). The wide spread of sulfur values in the ±7,100 kcal coal, ranging from 0.51% to 1.49% adb, points to uneven pyrite distribution, a phenomenon that has practical implications for stockpile management. Recent research on organic sulfur species in coal has shown that functional groups such as mercaptans, thioethers, and thiophenes exhibit different oxidation activities, with the order of oxidation activity from highest to lowest being mercaptan > thioether > thiophene (Wang et al., 2021). Because sulfur atoms are more easily oxidized than carbon atoms, C–S and S–H bonds are more susceptible to cleavage, yet most studies on sulfur's role in spontaneous combustion have focused on inorganic pyritic sulfur, while the contribution of organic sulfur species at low-temperature oxidation remains rarely reported. This gap underscores the need for more detailed sulfur speciation analysis in future studies at Stockpile 1.

The practical implications of this research are significant for coal stockpile management at PT Bukit Asam Tbk. and the broader Indonesian coal mining industry. First, prevention strategies cannot focus exclusively on sulfur content but must consider moisture and volatile matter as primary factors, especially for low-rank coals. Shan et al. (2026) emphasized the importance of systematic approaches to spontaneous combustion prevention in large-scale storage facilities, while Zhang and Sun (2022) documented practical measures for storage bunker prevention. The high mass loss of 90.12% observed in low-rank coal indicates that almost the entire volume of such coal can be lost due to spontaneous combustion, representing substantial economic losses. By recognizing that moisture and volatile matter are the dominant factors, companies can allocate resources toward drying or blending low-rank coals before long-term storage, as well as optimizing stacking geometry to enhance heat dissipation (Arisanti & Husni, 2025). Second, for high-rank coals with elevated sulfur content, sulfur monitoring remains important because of its role in degrading chemical quality and generating SO_2 emissions, even though the physical mass loss risk is lower. This dual approach, which differentiates between physical mass loss and chemical quality degradation, enables more targeted and cost-effective risk management. Third, the findings support the development of more accurate spontaneous combustion prediction models that assign greater weight to moisture and volatile matter for low-rank coals and to sulfur for high-rank coals, as also recommended by Onifade and Genc (2019) in their comprehensive review of spontaneous combustion prediction methods.

Despite its significant contributions, this study has several limitations that should be acknowledged. The experiments were conducted under controlled laboratory conditions using 10 kg samples over a 360-minute observation period, which may not fully capture the complex, long-term dynamics of spontaneous combustion in industrial-scale stockpiles where heat dissipation and aeration conditions differ substantially (Wu et al., 2024). However, the experimental design remains valid for studying fundamental mechanisms and making relative comparisons among coal types, an approach also adopted by Andryanto et al. (2025) and Wu et al. (2024). The study measured total sulfur without differentiating between organic, pyritic, and sulfate forms, even though recent research indicates that different sulfur species exhibit varying reactivity in low-temperature oxidation processes (Wang et al., 2021). Future research employing advanced analytical techniques such as X-ray diffraction or sulfur form analysis according to ASTM standards would provide deeper insights into the specific sulfur species contributing to spontaneous combustion. Additionally, the use of kerosene as a catalyst to initiate combustion may have accelerated the process and produced combustion patterns slightly different from natural spontaneous combustion, although such catalysts are commonly used in laboratory-scale studies to enable observation within practical timeframes (Andryanto et al., 2025). Finally, the study did not measure gas emissions (CO, CO_2, SO_2) during combustion, which could have provided additional information on oxidation mechanisms and early warning indicators of spontaneous combustion, as demonstrated by Arif et al. (2026), who showed that the CO_2/CO ratio can be a reliable indicator for monitoring spontaneous combustion tendency. Despite these limitations, the study makes a valuable contribution by quantitatively revealing the relationship between total sulfur and coal loss due to spontaneous combustion at the specific location of PT Bukit Asam Tbk., an area that has received limited research attention, and by providing actionable insights for improving stockpile management practices.

CONCLUSION

This study tested four coal types with different calorific values: ±4,200 kcal, ±4,900 kcal, ±5,300 kcal, and ±7,100 kcal. The spontaneous combustion simulation ran for 360 minutes. Mass and temperature were recorded every 30 minutes.

Total Sulfur content rose as calorific value increased. The ±4,200 kcal coal averaged 0.12% TS (adb). The ±7,100 kcal coal averaged 1.05% TS (adb). Sulfur distribution in high-calorie coal fluctuated far more than in low-calorie coal.

The combustion results showed an inverse pattern. The coal with the lowest sulfur content (±4,200 kcal) lost the most mass, 90.12% of its starting weight, at a peak temperature of 684.07°C. The coal with the highest sulfur content (±7,100 kcal) lost the least mass, 71.82%, at a peak temperature of only 523.42°C. Sulfur content, therefore, does not drive the rate of physical mass loss during spontaneous combustion.

Total Moisture drives that rate instead. Low-calorie coal holds a high moisture content (36.64%). This moisture evaporates fast under heat, opens up the coal's pores, and triggers rapid oxidation. This process dominates mass loss and masks sulfur's effect. High-calorie coal holds low moisture (6.80%), which gives it better thermal stability. Under these stable conditions, sulfur's effect becomes clearer. It degrades coal quality and drives SO_2 emissions.

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The author recognizes this journal still has shortcomings. Feedback and suggestions from readers are welcome for future improvement. The author hopes this journal contributes to the field and serves as a reference for future research.

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