THE EFFECT OF RAINFALL ON THE GROSS CALORIFIC VALUE OF COAL (CASE STUDY AT PT KALIMANTAN PRIMA PERSADA, RANT SITE)

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Abstract. *Coal is an energy source whose quality can be influenced by environmental factors, particularly rainfall. This study aims to analyze the correlation between rainfall intensity and total moisture content, as well as its impact on the Gross Calorific Value (GCV) of coal at PT Kalimantan Prima Persada. The data used in this study includes daily rainfall data (mm), and test results of inherent moisture (%) and GCV (kcal/kg), collected over a two-month period from November to December 2024. A total of 30 coal samples were analyzed to determine the relationship between rainfall and total moisture content, as well as its effect on GCV. The collected data were analyzed using regression methods. The results indicate that increased rainfall is directly proportional to the increase in coal's total moisture content, with an R^2 value of 0.8205, indicating that approximately 82.05% of the variability in total moisture can be explained by rainfall. Additionally, the study discusses the impact of total moisture on GCV. The comparison results show that total moisture has a more significant effect, with an R^2 value of 0.827, indicating that 82.7% of the variation in calorific value can be attributed to total moisture. These findings are expected to assist the mining industry in implementing better coal protection and storage strategies to maintain coal quality.*

Keywords: *Coal, Gross Calorific Value, Mining, Moisture, Mining, Rainfall*

1. INTRODUCTION

Indonesia is known as one of the countries with the largest coal reserves in the world, making it one of the leading exporters of this energy commodity. Coal, one of the fossil fuels used by humans for centuries, plays a significant role in the global energy sector. In the coal industry, maintaining quality is a critical aspect, as the quality of coal directly determines its economic value and efficiency as a fuel. Several key factors influence coal quality, including moisture content, carbon content, ash content, volatile matter, and sulfur content. Moisture in coal is generally classified into two types: inherent moisture, which is naturally bound within the coal structure, and free moisture, which is absorbed from the external environment, such as through rainfall (Hidayah & Norfaeda, 2020).

Indonesia's geographical and tropical climatic conditions, particularly at the RANT mining site, make rainfall an environmental factor that cannot be overlooked. During the rainy season, high rainfall intensity significantly increases coal moisture content, especially free moisture, as coal tends to absorb water when exposed to open air. This phenomenon commonly occurs during stockpiling and transportation processes, affecting both the weight and quality of the coal produced. Rainfall refers to the amount of water falling to the earth's surface in the form of rain, snow, or hail, typically measured in millimeters (mm) over a specific period. Rainfall intensity is the amount of water falling per unit of time, while rainfall duration refers to the length of time precipitation occurs. These two factors determine the extent to which rainfall impacts human activity and the environment (Chow et al., 1988). Previous studies have shown that high rainfall can increase coal moisture content by up to 32.39% during the stockpiling process (Hidayah & Norfaeda, 2020).

High moisture content not only affects coal quality but also reduces the Gross Calorific Value (GCV), which is a primary indicator of combustion efficiency. The higher the moisture content, the lower the GCV, thereby decreasing the potential energy output of the coal. Another impact is the increase in operational costs, particularly in transportation, since wet coal weighs more than dry coal, placing additional financial burdens on mining companies (Rianto, 2022).

PT Kalimantan Prima Persada at the RANT site, as one of the coal mining companies in Indonesia, faces similar challenges, particularly during the rainy season. High rainfall intensity can significantly impact coal quality. Therefore, understanding how environmental factors such as rainfall affect the Gross Calorific Value (GCV) of coal is crucial. This study is designed to explore the environmental and physical characteristics of coal at the RANT site. The findings are expected to contribute to improving the operational efficiency of the company while maintaining the quality of its coal products.

2. LITERATURE REVIEW

2.1 Coal

Coal is one of the fossil energy sources that has been used by humans for centuries. It has a long history, unique characteristics, a wide range of applications, and presents certain challenges in its utilization. Coalification is a geological process that occurs over millions of years, transforming organic material such as ancient plant matter into coal due to high pressure and temperature beneath the Earth's surface. This process involves several major stages, including peat, lignite, sub-bituminous, bituminous, and anthracite, with anthracite being the form of coal that contains the highest carbon content and the lowest moisture level (Ward, 2002).

The initial stage begins with the decomposition of plant material in oxygen-deficient swamp environments, forming peat. As layers of peat become buried by sediments, they undergo pressure and heat over millions of years, resulting in the formation of lignite, or brown coal. Over a longer period, lignite may further evolve into sub-bituminous, bituminous, and eventually anthracite coal each with progressively higher Gross Calorific Value (GCV) (Suárez-Ruiz & Crelling, 2008).

The physical and chemical characteristics of coal vary and significantly affect its quality and suitability as a fuel. These characteristics include the following.

2.1.1 Carbon Content and Gross Calorific Value (GCV)

One of the key factors that determines coal quality and combustion efficiency is its carbon content. A higher carbon content indicates a greater amount of energy produced per unit mass of coal. The Gross Calorific Value (GCV) of lignite or sub-bituminous coal is lower than that of coal with a higher carbon content, such as anthracite (Ward, 2002). GCV is a measure of the energy released when coal is burned. This value is crucial in assessing the efficiency of coal as a fuel. Lignite with low carbon content generates lower energy, while coal with carbon content above 90% produces the highest GCV (Speight, 2012).

2.1.2 Moisture Content

There are three main types of moisture found in coal. Free moisture refers to the water present on the surface of coal due to exposure to rain or ambient humidity. Inherent moisture is the water that is naturally bound within the internal structure of the coal. Total moisture represents the overall water content in coal, including both free and inherent moisture.

High moisture content can reduce the Gross Calorific Value (GCV) of coal, as the water absorbs part of the energy during combustion through evaporation. Additionally, the increased weight of wet coal results in higher transportation costs due to greater mass in movement (Sami et al., 2001). According to Speight (2012), high moisture content can significantly reduce the efficiency of coal utilization in power plants.

2.1.3 Ash Content

Ash is the inorganic residue left after coal combustion. A high ash content generally indicates a significant presence of mineral matter in the coal, which lowers combustion efficiency and increases waste management costs. Furthermore, the remaining ash can cause fouling or slagging in boilers, requiring additional maintenance (Suárez-Ruiz & Crelling, 2008).

2.1.4 Sulfur Content

Coal contains sulfur in both organic and inorganic forms. During combustion, sulfur is released as sulfur dioxide (SO_2), which can be harmful to the environment. SO_2 emissions contribute to acid rain and air pollution. Therefore, desulfurization technologies or the use of low-sulfur coal are essential for environmentally responsible power generation operations (Sami et al., 2001).

2.1.5 Volatile Matter Content

When coal is heated in the absence of air, compounds known as volatile matter are released, including hydrocarbons, carbon dioxide, and other gases. Coal with high volatile matter content is generally easier to ignite but may also produce higher emissions (Speight, 2012).

2.1.6 Coal Types Based on Quality

Coal is classified based on its degree of coalification or rank, which reflects the physical and chemical changes during the formation process. This rank is influenced by factors such as pressure, temperature, and time. The classification system developed by the U.S. Bureau of Mines, later adopted by the American Society for Testing and Materials (ASTM), categorizes coal according to its degree of metamorphism, ranging from lignite to anthracite. To determine coal rank, data on fixed carbon, volatile matter, and Gross Calorific Value (GCV) in Btu/lb are required. In general, based on the degree of coalification and physico-chemical properties, coal is grouped into various classes as presented in Table 1.

Table 1. ASTM D388-12 Specifications for Solid Fuels

Class	Group		Fixed Carbon	Volatile Matter	Heating Values
	Name	Symbol	Dry (%)	Dry (%)	Dry Basis (Kcal/kg)
I. Anthracite	Meta-anthracite	ma	>98	>2	7740
	Anthracite	an	92-98	2.0-8.0	8000
	Semi-anthracite	sa	86-92	8.0-15	8300
II. Bituminous	Low-volatile	lvb	78-86	14-22	8741
	Medium volatile	mvb	89-79	22-31	8640
	High-volatile A	hvAb	<69	>31	8160
	High-volatile B	hvBb	57	57	6750-8160
	High-volatile C	hvCb	54	54	7410-8375
					6765-7410
III. Sub-bituminous	Sub-bituminous A	subA	55	55	6880-7540
	Sub-bituminous B	subB	56	56	6540-7230
	Sub-bituminous C	subC	53	53	5990-6860
IV. Lignite	Lignite A	ligA	52	52	4830-6360
	Lignite B	ligB	52	52	<5250

2.2 Rainfall

As one of the main components of the hydrological system, rainfall plays a crucial role in various aspects of life, including agriculture, water resources, and industrial activities. In the mining sector, rainfall can pose significant challenges as it affects multiple operations such as excavation, material storage, and transportation. This section provides a comprehensive overview of rainfall and its patterns in Indonesia, particularly in South Kalimantan, as well as its impact on mining activities.

Rainfall refers to the amount of water that falls to the Earth's surface in the form of rain, snow, or hail, and is typically measured in millimeters (mm) over a specific period. Rainfall intensity is the measurement of water volume falling per unit of time, while rainfall duration refers to the length of time precipitation occurs. These two factors determine how rainfall affects human activities and the environment (Chow et al., 1988).

2.3 Sampling Method

Sampling is a critical stage that significantly influences the quality of analytical results. The primary objective of sampling is to obtain a representative portion of a material population, such as ore, coal, or soil, for further testing. Inaccuracies or errors during the sampling process may lead to biased data, which in turn compromises the validity of the analysis and the reliability of interpretations.

This study employed the random sampling method, in which every element within the population has an equal probability of being selected. The strength of this method lies in its ability to minimize sampler bias and its relatively straightforward application, particularly when the material under investigation is homogeneous. Nevertheless, random sampling may prove inefficient when applied to highly heterogeneous populations or materials with uneven distribution. To ensure proper randomness, auxiliary tools such as a random number generator or a systematic manual randomization approach are generally required.

2.4 Coal Moisture Measurement Methods

One of the critical steps in determining the quality and economic value of coal is measuring its moisture content. The moisture content in coal directly affects its Gross Calorific Value (GCV), transportation costs, and combustion efficiency. Therefore, accurate measurement is essential to ensure the quality of coal prior to its utilization or sale. The following section provides a detailed overview of the methods, equipment, and testing standards used to measure coal moisture content.

2.4.1 Moisture Content in Coal

Moisture content is one of the key parameters influencing the quality and efficiency of coal as a fuel. Coal moisture is generally categorized into three main types: inherent moisture, free moisture, and total moisture. Inherent moisture refers to the water naturally bound within the coal's microstructure, which is difficult to evaporate. Free moisture is the water present on the coal surface due to environmental exposure, such as rainfall or ambient humidity. The combination of inherent and free moisture is referred to as total moisture, representing the overall water content in the coal (Speight, 2012).

2.4.2 Techniques and Instruments for Moisture Measurement

Several specialized techniques and instruments are employed to measure coal moisture content accurately in accordance with industrial requirements. One of the most commonly used techniques is the oven-drying method, in which coal samples are dried in an oven at approximately 105°C until a constant weight is achieved. This method is widely recognized for its accuracy in determining total moisture. However, it is relatively time-consuming and may not be ideal for field applications.

2.4.3 Testing Standards for Moisture Measurement

To ensure that results are accurate, consistent, and globally comparable, coal moisture measurements must comply with international testing standards. These standards provide comprehensive guidelines regarding procedures, equipment, and conditions required for reliable measurements. Two internationally recognized ASTM standards are ASTM D3173 and ASTM D1412.

ASTM D3173 is used to determine the total moisture content in a coal sample by drying it in an oven at 105°C until a constant weight is reached. This method is highly regarded for its precision in measuring total moisture.

ASTM D1412, on the other hand, is employed to measure inherent moisture—the chemically bound water in coal. This measurement is performed by drying the sample at a lower temperature that does not alter the coal's organic structure.

The use of international standards is essential to meet technical specifications required by customers or global markets. It ensures that the testing procedures are validated and that results obtained from different laboratories are reliable and comparable.

2.5 Coal Calorific Value Measurement Method

The calorific value is a critical parameter in determining the quality of coal as an energy source. It indicates the amount of energy released when coal is combusted completely. The higher the Gross Calorific Value (GCV) of coal, the greater the amount of energy produced per unit mass. GCV is influenced by several factors, including fixed carbon content, volatile matter, moisture, and ash content. Therefore, its measurement is essential in industries such as power generation, manufacturing, and other energy-related sectors.

The most widely used and accurate method for measuring the Gross Calorific Value of coal is the bomb calorimeter technique. This method involves combusting a coal sample in a sealed vessel (bomb calorimeter) filled with pure oxygen. During combustion, the heat generated is absorbed by the surrounding water, and the resulting temperature change is used to calculate the coal's GCV. This technique is highly accurate and is considered a standard in the industry, as defined by ASTM D5865 and ISO 1928. However, its limitations include high equipment costs and relatively long analysis times (Gupta & Ghosh, 2020).

3. RESEARCH METHODS

The research was conducted using secondary data obtained from a proximate analysis testing laboratory and from a monitoring control system. The collected data included the inherent moisture content in coal as well as rainfall information relevant to the research location. The secondary data were processed using Microsoft Excel software. The method employed for analyzing the data was regression analysis.

In the implementation of this final project research, a series of systematic steps were necessary to achieve results that are both valid and reliable. This process included several phases, starting from literature review, data collection, data processing, and data analysis, to the final report preparation. The research process flowchart is presented in Figure 1, and the tools and materials used are listed in Table 2.

Table 2. Research Tools and Materials

Tools	:	Shovel, Sample Plastic Bags, Jaw Crusher, Rotary Sample Divider, Pulverizer, Sieve Shaker, Oven, Crucible, Analytical Balance, Furnace, Bomb Calorimeter
Material	:	Coal Samples

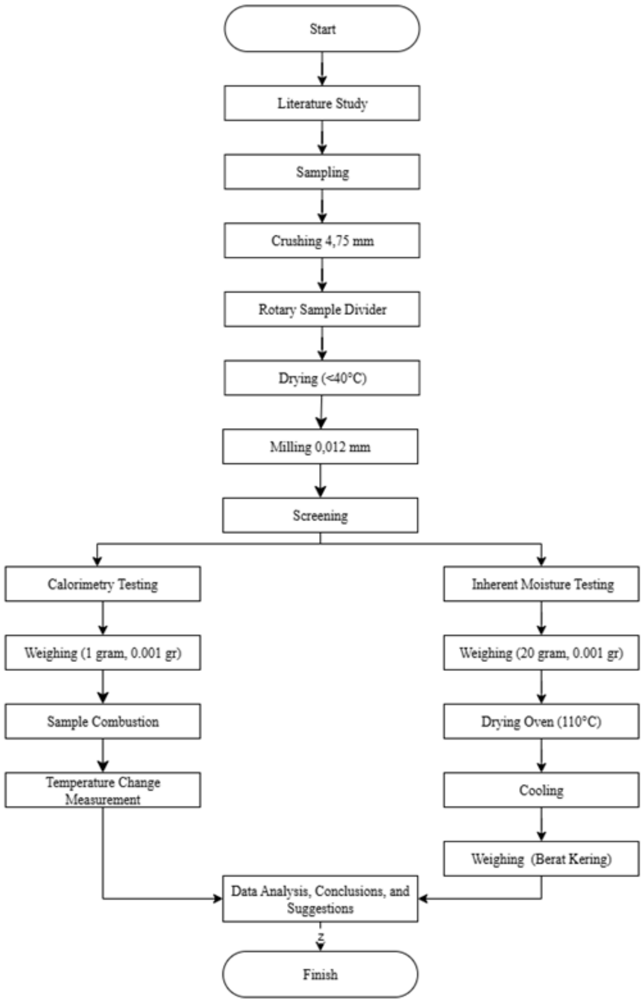

Figure 1. Research Flowchart

The data collected consisted of Air-Dry Loss (ADL), Inherent Moisture (IM), ash content, calorific value, and rainfall data at the research area, namely PT Kalimantan Prima Persada, RANT site. The testing was conducted periodically from November 1 to December 4, 2024, on coal samples obtained from the coal size reduction area. The results of the IM and calorific value tests are presented in Table 3.

Table 3. Proximate Analysis Data: Inherent Moisture and Calorimetry

No	Data	ADL	IM (%)	GCV (kcal/kg)
			ar	adb
1	01/11/2024	22,5	17,4	5266
2	02/11/2024	21,65	17,48	5317
3	03/11/2024	22,5	18,06	5192
4	04/11/2024	22,25	16,64	5371
5	06/11/2024	21,88	17,47	5289
6	07/11/2024	21,88	18,17	5263
7	08/11/2024	21,38	20,84	5106
8	09/11/2024	20	20,74	5141
9	10/11/2024	18,75	21,84	5075
10	11/11/2024	21	17,86	5288
11	12/11/2024	20,63	18,49	5270
12	15/11/2024	20,63	18,92	5262
13	16/11/2024	20,63	18,8	5254

No	Data	ADL	IM (%)	GCV (kcal/kg)
			ar	adb
14	17/11/2024	20,63	18,66	5256
15	18/11/2024	22,5	17,68	5332
16	19/11/2024	22,5	16,64	5421
17	20/11/2024	21,88	17,33	5336
18	21/11/2024	22,5	18,1	5288
19	22/11/2024	18,75	21,23	5078
20	23/11/2024	21,13	18,01	5310
21	24/11/2024	21,75	17,58	5330
22	26/11/2024	23,63	15,69	5467
23	27/11/2024	20,63	19,82	5204
24	28/11/2024	20,63	19,38	5234
25	29/11/2024	22,5	16,88	5366
26	30/11/2024	23,13	17,3	5324
27	01/12/2024	21,88	18,51	5236
28	02/12/2024	22,5	18,68	5251
29	03/12/2024	23,13	16,66	5372
30	04/12/2024	21,13	19,02	5255

Rainfall data were obtained from the monitoring control system operating at the mining site. Monitoring was conducted automatically using rain gauges installed at several strategic points within the mining area. The collected data include daily rainfall intensity, recorded in millimeters (mm). The daily rainfall intensity data are presented in Table 4.

Table 4. Daily Rainfall Data

Data	*site*	Curah Hujan (mm)
01/11/2024	RANT	3,00
02/11/2024	RANT	0,50
03/11/2024	RANT	12,00
04/11/2024	RANT	0,00
06/11/2024	RANT	1,00
07/11/2024	RANT	5,50
08/11/2024	RANT	60,50
09/11/2024	RANT	21,00
10/11/2024	RANT	19,00
11/11/2024	RANT	0,00
12/11/2024	RANT	0,00
15/11/2024	RANT	2,50
16/11/2024	RANT	1,50
17/11/2024	RANT	0,50
18/11/2024	RANT	10,00
19/11/2024	RANT	0,50
20/11/2024	RANT	0,50
21/11/2024	RANT	0,00
22/11/2024	RANT	4,00
23/11/2024	RANT	0,00
24/11/2024	RANT	1,00
26/11/2024	RANT	2,00
27/11/2024	RANT	11,50
28/11/2024	RANT	5,50
29/11/2024	RANT	1,50
30/11/2024	RANT	11,50
01/12/2024	RANT	10,00
02/12/2024	RANT	28,00

Data	*site*	Curah Hujan (mm)
03/12/2024	RANT	3,00
04/12/2024	RANT	9,50

The data collected from both sources were then compiled and analyzed. Rainfall data were compared with total moisture data obtained from laboratory analysis in order to identify patterns of correlation between rainfall intensity and total moisture content in coal. The analysis was conducted using descriptive statistical methods and regression analysis to determine the correlation between the two variables.

After the data were obtained, the next step was data processing to generate analytical results that could be used for further discussion. The following is an explanation of the data processing procedure.

The first step in data processing was to calculate the Total Moisture (TM) content in coal. Total moisture was calculated based on the values of Inherent Moisture (IM) and Air-Dried Loss (ADL) using the formula presented in Equation (1):

$$TM = ADL + IM\ x\ (\frac{1 - ADL}{100})$$

The next step was to calculate the Gross Calorific Value (GCV) on an as-received (ar) basis. Since the calorific value obtained from the calorimetric analysis was on an air-dried basis (adb), the conversion to as-received (ar) was necessary to evaluate the effect of total moisture on calorific value. The GCV on an as-received basis was calculated using the formula shown in Equation (2).

$$GCV_{ar} = \frac{100 - TM}{100 - IM}\ x\ GCV_{adb}$$

Once the total moisture value had been obtained, simple linear regression analysis was performed to assess the relationship between rainfall intensity and total moisture, total moisture and calorific value, as well as ash content and calorific value. The regression model used is presented in Equation (3):

$$Y = a + bX$$

4. RESULTS AND DISCUSSION

4.1 Analysis Results

The results obtained from the simple linear regression analysis regarding the effect of rainfall intensity on total moisture are presented in Table 5. The Multiple R value indicates the strength of the relationship between the independent and dependent variables. A value of 0.906 was obtained, which signifies a very strong correlation. The R Square value represents how much of the variation in total moisture can be explained by rainfall. An R Square of 0.820 (or 82%) indicates that rainfall significantly affects total moisture content, while the remaining 18% is influenced by other factors. The Significance F value is used to determine whether the relationship between rainfall and total moisture is statistically significant or if it occurs merely by chance.

Table 5. Simple Linear Regression Analysis of the Effect of Rainfall on Total Moisture

Regression Analysis	
Multiple R	0,905808212
R Square	0,820488517
Significance F	2,54702E-11
Observations	30

The regression equations can be derived using the formulas presented in Equation (4) and Equation (5). The resulting regression equation obtained from the analysis of the effect of rainfall on total moisture is presented in Equation (6).

$$a = \frac{(\sum Y)\ (\sum X^2)\ -\ (\sum X)\ (\sum XY)}{n\ .\sum X^2\ -\ (\sum X)^2}$$

$$b = \frac{n.\sum XY - (\sum X)(\sum Y)}{n.\sum X^2 - (\sum X)^2}$$

$$TM = 35{,}548 + 0{,}045\,CH$$

After confirming that rainfall intensity significantly affects total moisture, a subsequent regression analysis was conducted to examine how total moisture influences the Gross Calorific Value (GCV). The model used follows the same structure as presented in Equation (3).

The results of the regression analysis are shown in Table 6, which presents the relationship between total moisture and calorific value. The regression results indicate an R value of 0.909, suggesting a strong correlation between total moisture and calorific value. In addition, the coefficient of determination (R^2) is 0.827, indicating that 82.7% of the variation in calorific value can be explained by total moisture. Furthermore, the Significance F value of 1.25535E-10 demonstrates that the regression model is highly statistically significant in explaining the relationship between total moisture and calorific value. The resulting regression equation for the effect of total moisture on calorific value is presented in Equation (7).

Table 6. Regression Analysis of the Effect of Total Moisture (TM) on Gross Calorific Value (GCV)

Analisis Regresi	
Multiple R	0,909488604
R Square	0,82716952
Significance F	8,47689E-12
Observations	30

$$GCV = 6581{,}56 - 68{,}08 \cdot \mathrm{TM}$$

4.2 Discussion

One of the main factors affecting coal quality is its moisture content, which consists of Inherent Moisture (IM) and Total Moisture (TM). High moisture content has a negative impact on the Gross Calorific Value (GCV), as the water present in coal absorbs energy during combustion, thereby reducing the efficiency of energy generation (Jorjani & Chelgani, 2009; Matin & Chelgani, 2016). Several studies have shown that the higher the moisture content, the lower the GCV of coal, which in turn affects the combustion efficiency in power generation systems (Bhatt & Rajkumar, 2015; Chen et al., 2024).

At PT Kalimantan Prima Persada, RANT site, rainfall intensity is an external factor that can contribute to increased coal moisture content. High rainfall has the potential to raise free moisture levels in coal stored in open stockpiles. Therefore, this study aimed to analyze the relationship between rainfall intensity and moisture content, as well as its impact on the calorific value of coal.

An analysis was conducted to determine the effect of rainfall on total moisture content in coal at the RANT site. Based on the processed data, a positive correlation was found between rainfall and coal moisture content. The regression analysis shown in Table 3.1 reports a Multiple R value of 0.906, indicating a very strong relationship between the independent and dependent variables. Furthermore, the R Square value was 0.820, meaning that 82% of the variation in total moisture content can be explained by rainfall, while the remaining 18% may be attributed to other influencing factors. This relationship is further illustrated in Figure 2.

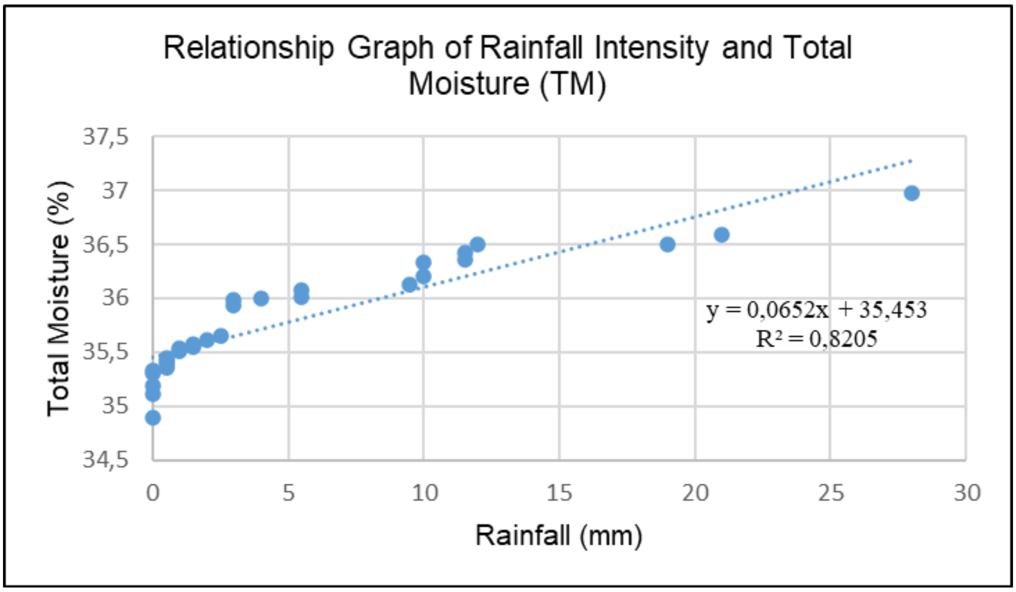

Figure 2. Graph of the Relationship Between Rainfall Intensity and Total Moisture

As rainfall increases, the likelihood of coal absorbing moisture also rises, thereby increasing its total moisture content. This finding is consistent with previous research by Zhang et al. (2021), which demonstrated that coal exposure to rainfall leads to elevated moisture levels, ultimately affecting both the quality and combustion efficiency of the coal. The increase in moisture content reduces the Gross Calorific Value (GCV) because a portion of the energy produced during combustion is used to evaporate the moisture rather than generate useful heat (Jorjani & Chelgani, 2009). Moreover, high moisture levels can result in incomplete combustion, contributing to higher emissions of greenhouse gases such as carbon monoxide (CO) and methane (CH_4), and increasing the production of ash residue (Matin & Chelgani, 2016).

Combustion quality and efficiency are critical, as they directly affect the performance of industries that rely on coal as an energy source, such as power generation and manufacturing sectors. Low combustion efficiency leads to higher coal consumption to produce the same amount of energy, ultimately increasing operational costs and dependence on fossil fuels (Bhatt & Rajkumar, 2015). Additionally, reduced coal quality negatively impacts the environment, as incomplete combustion releases greater quantities of air pollutants such as sulfur dioxide (SO_2) and fine particulate matter (PM2.5), which contribute to public health issues and environmental degradation (Chen et al., 2024).

In addition to its impact on total moisture, high water content in coal directly affects its calorific value. The relationship between total moisture and Gross Calorific Value (GCV) is illustrated in Figure 3.

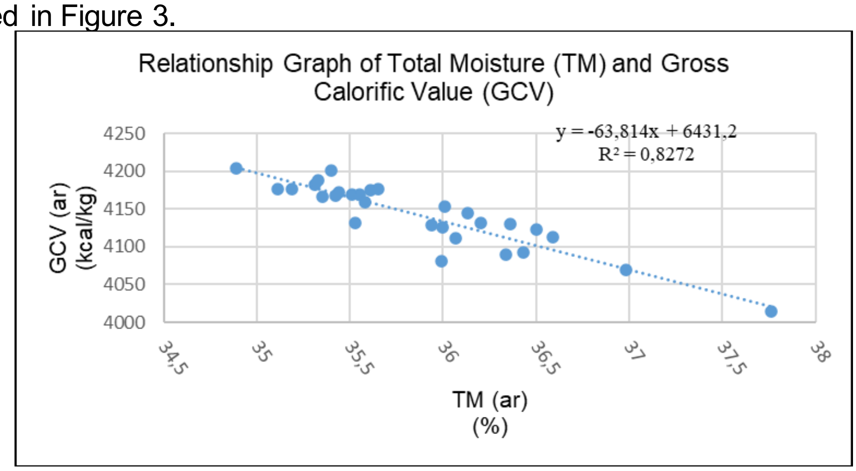

Figure 3. Graph of the Relationship Between Total Moisture and Gross Calorific Value (GCV)

This relationship is further supported by the simple linear regression analysis of the effect of total moisture on calorific value (GCV), as presented in Table 3.2. The regression result shows a Multiple R value of 0.909, indicating a strong correlation between total moisture and calorific value. Additionally, the coefficient of determination (R^2) is 0.827, meaning that 82.7% of the variation in GCV can be explained by the variation in total moisture.

The interpretation of Equation 7 suggests that for every 1% increase in Total Moisture (TM), the Gross Calorific Value (GCV) decreases by approximately 63.814 kcal/kg. The interpretation of Equation 10 indicates that for every 1% increase in Total Moisture (TM), the Gross Calorific Value (GCV) decreases by approximately 63.814 kcal/kg. This can be explained by the fact that the water contained in the coal absorbs part of the heat generated during the combustion process, thereby reducing the amount of energy released. Table 7 presents a comparison of the reduction in GCV resulting from variations in TM.

Table 7. Comparison of Total Moisture (TM) Increase and Its Effect on Gross Calorific Value (GCV)

This Study	Hernanto et al., (2020)	Liu et al., (2019)
A 1% increase in total moisture (TM) reduces GCV by 63.814 kcal/kg.	A 1% increase in total moisture may cause a reduction in GCV of up to 123.36 kcal/kg.	A 1% increase in total moisture may result in a decrease in GCV by approximately 4–5 kcal/kg.

The reduction in Gross Calorific Value (GCV) resulting from a 1% increase in Total Moisture (TM) may vary across coal samples due to the physical and chemical characteristics of the coal. This variability can be attributed to differences in the composition of mineral impurities, pore structure and surface area, coal type and rank, as well as the distribution form of moisture within the sample. These factors indicate that not all coal will respond to additional moisture in the same way, highlighting the importance of thoroughly characterizing coal in energy and combustion studies.

The total moisture content has a significant influence on the reduction of coal's Gross Calorific Value (GCV), as demonstrated by the results of the regression analysis. This indicates that the higher the moisture content in coal, the lower the GCV produced. Increases in both moisture and ash content can be attributed to several contributing factors. Regarding moisture, one of the primary causes is the hygroscopic nature of coal, which refers to its ability to absorb water vapor from the surrounding air. The higher the hygroscopicity, the greater the coal's potential to absorb ambient moisture.

In addition, open storage conditions significantly affect moisture accumulation. When coal is stored in uncovered or unprotected areas, it becomes highly susceptible to water absorption from rainfall and atmospheric humidity, particularly in regions with high precipitation. This accumulation directly increases the total moisture content of the coal.

One of the primary methods to mitigate moisture uptake is through enclosed storage systems, such as coal sheds or dome storage facilities, which prevent direct exposure to rain. According to Zhang et al. (2018), storing coal in enclosed facilities can reduce moisture buildup by up to 70% compared to open storage. Moreover, effective drainage systems in storage areas are essential to prevent water pooling, which can further raise moisture content (Liu et al., 2020). In coal stockpile management, rotation practices are equally crucial. Older coal is more susceptible to moisture accumulation; therefore, a First In, First Out (FIFO) system should be implemented to ensure that older coal is utilized before newer batches (Sun, 2020).

Coal with high hygroscopic properties tends to absorb ambient moisture, especially in areas with high relative humidity. As a result, the implementation of coal pre-drying technologies has become an effective solution for reducing moisture prior to combustion.

Xie et al. (2019) found that thermal drying methods can decrease moisture content by up to 50% and improve combustion efficiency by 15%.

In addition to storage and handling factors, coal particle size also plays a role in moisture content. Finer coal particles have a greater specific surface area, making them more prone to moisture absorption (Sun, 2020). Liu et al. (2020) discovered that coal particles under 6 mm tend to retain more water due to higher capillarity. Moreover, fine coal particles are more difficult to separate from ash-forming minerals, leading to higher ash content in smaller-sized coal (Chatterjee, 2018).

In mining operations, a Double Roll Crusher (DRC) is commonly used to produce uniform coal sizes. The output size typically ranges from 10 to 50 mm, which is considered optimal for combustion and transport processes in coal-fired power plants (Zhang et al., 2019). When coal is crushed to sizes smaller than 10 mm, moisture tends to increase due to the expanded surface area and water retention effects. Conversely, when the size exceeds 50 mm, combustion becomes less efficient due to reduced surface contact with air. Therefore, controlling coal particle size is essential in quality management prior to delivery to end users.

In conclusion, improvements in coal storage systems and handling practices are vital, as environmental conditions and storage management have the most significant influence on increasing coal moisture content and decreasing Gross Calorific Value (GCV). The strategies outlined above have been proven effective in previous studies and may serve as practical guidelines for enhancing coal quality across various industrial sectors.

CONCLUSION

This study concludes that rainfall directly contributes to the increase in moisture content, which consequently affects the reduction of the Gross Calorific Value (GCV) of coal. Based on the findings and analyses conducted throughout the research, the main conclusions can be summarized as follows: 1) The results indicate that rainfall has a positive correlation with the total moisture content in coal. From the simple linear regression analysis, the equation obtained is:TM = 35.548 + 0.045CH, where TM is Total Moisture and CH is Cumulative Rainfall. The coefficient of determination (R^2) is 0.820, indicating that rainfall can explain 82% of the variation in total moisture, while the remaining 18% is influenced by other factors; 2) A high moisture content in coal negatively impacts its quality, particularly its Gross Calorific Value (GCV). From the simple linear regression analysis, the following equation was obtained: GCV = 6581.56 − 68.08·TM, where GCV is the Gross Calorific Value and TM is Total Moisture. The coefficient of determination (R^2) is 0.827, which means that 82.7% of the variation in GCV can be explained by changes in total moisture content, while the remaining 17.3% is attributed to other influencing factors.

REFERENCES

ASTM International. (2012). *ASTM D388-12: Standard classification of coals by rank*. ASTM International. https://doi.org/10.1520/D0388-12

ASTM International. (2021). *ASTM D3173-21: Standard test method for moisture in the analysis sample of coal and coke*. ASTM International. https://doi.org/10.1520/D3173-21

ASTM International. (2022). *ASTM D1412-22: Standard test method for equilibrium moisture of coal at 96 to 97 percent relative humidity and 30 °C*. ASTM International. https://doi.org/10.1520/D1412-22

ASTM International. (2023). *ASTM D5865-23: Standard test method for gross calorific value of coal and coke*. ASTM International. https://doi.org/10.1520/D5865-23

Bhatt, M., & Rajkumar, N. (2015). Effect of moisture in coal on station heat rate and fuel cost for Indian thermal power plants. *Journal of CPRI*. https://www.researchgate.net/publication/301771215_Effect_of_moisture_in_coal_on_station_heat_rate_and_fuel_cost_of_Indian_thermal_power_plants

Chatterjee, A. (2018). *Coal preparation and utilization*. CRC Press.

Chen, J., He, Y., Liang, Y., Wang, W., & Duan, X. (2024). Estimation of gross calorific value of coal based on the cubist regression model. *Scientific Reports*. https://www.nature.com/articles/s41598-024-74469-3

Chow, V. T., Maidment, D. R., & Mays, L. W. (1988). *Applied hydrology*. McGraw-Hill Education.

Gupta, R., & Ghosh, S. (2020). Calorific value determination of coal using bomb calorimetry: A comprehensive review. *Fuel Processing Technology, 205,* 106431. https://doi.org/10.1016/j.fuproc.2020.106431

Hernanto, A., Pitulima, J., & Andini, D. (2020). Analisis pengaruh perubahan nilai total moisture dan ash content terhadap nilai kalori batubara di Unit Pelabuhan PT Bukit Asam Tbk Tarahan Bandar Lampung. *Jurnal Mineral, 5*(1), 7–12.

Hidayah, N., & Norfaeda, R. (2020). Studi pengaruh perubahan suhu terhadap nilai total moisture batubara produk E4700 di PT. Adaro Indonesia Site Kelanis, Kalimantan Tengah. *Jurnal GEOSAPTA.*

Jorjani, E., & Chelgani, S. C. (2009). Estimation of gross calorific value based on coal analysis using regression and artificial neural networks. *International Journal of Coal Geology.*

Liu, J., Wang, Y., & Zhao, H. (2019). Effect of moisture content on the calorific value of coal. *Energy & Fuels, 34*(2), 223–234.

Liu, Y., Zhang, W., & Chen, X. (2020). Investigation on moisture removal from coal using mechanical dewatering techniques. *Fuel Processing Technology, 205,* 106–118. https://doi.org/10.1016/j.fuproc.2020.106118

Matin, S. S., & Chelgani, S. C. (2016). Estimation of coal gross calorific value based on various analyses by random forest method. *Fuel.* https://www.sciencedirect.com/science/article/pii/S0016236116300680

Rianto, D. J. (2022). Analisis pengaruh kandungan air (total moisture) batubara terhadap nilai kalori batubara di front penambangan. *Formosa Journal of Multidisciplinary Research.* https://journal.formosapublisher.org/index.php/fjmr/article/download/582/454

Sami, M., Annamalai, K., & Wooldridge, M. (2001). Co-firing of coal and biomass fuel blends. *Progress in Energy and Combustion Science, 27*(2), 171–214.

Speight, J. G. (2012). *The chemistry and technology of coal*. CRC Press.

Suárez-Ruiz, I., & Crelling, J. C. (2008). *Applied coal petrology*. Academic Press.

Sun, H. (2020). Effect of coal moisture on combustion performance and boiler efficiency in thermal power plants. *Energy Reports, 6,* 1024–1032. https://doi.org/10.1016/j.egyr.2020.04.028

Ward, C. R. (2002). Analysis and significance of mineral matter in coal seams. *International Journal of Coal Geology, 50*(1–4), 135–168.

Xie, W., Wang, L., & Zhao, Y. (2019). Experimental study on pre-drying treatment for high moisture coal. *Applied Thermal Engineering, 152,* 223–232. https://doi.org/10.1016/j.applthermaleng.2019.02.008

Zhang, J., Li, P., & Wei, H. (2018). Impact of coal storage methods on moisture content and calorific value. *Fuel Science and Technology, 196,* 34–47. https://doi.org/10.1016/j.fst.2018.09.012

Zhang, J., Liu, H., & Zhao, T. (2019). Effect of coal blending on kandungan abu composition and combustion efficiency. *Fuel Processing Technology, 187,* 120–134. https://doi.org/10.1016/j.fuproc.2019.02.012

Zhang, Q., Sun, R., & Zhao, T. (2021). Impact of rainfall exposure on coal moisture and combustion properties. *International Journal of Coal Science & Technology, 8*(4), 300–315.