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RESEARCH ARTICLE

An Environmental Study of Coal Sedimentation in the Leban Muara Bungo Area of Jambi and a Prediction of Its Quality Distribution

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Abstract

Coal quality is affected by the depositional environment, characteristics of organic matter, and input of clastic sediments during peat formation. Although the link between depositional environment and coal quality has been widely studied in various coal basins, research that combines petrographic analysis, coal facies (TPI-GI and VI-GWI), coal quality, and geostatistics to assess the geological control over coal quality distribution in the Sinamar Formation remains very limited. This study aims to interpret the coal deposition environment of Seam C and analyze how the deposition environment relates to variations in coal quality in the Leban area, Jambi Province. The methods involved proximate and ultimate analysis, petrography, coal facies interpretation using the Tissue Preservation Index (TPI), Gelification Index (GI), Vegetation Index (VI), and Groundwater Index (GWI), along with descriptive statistics and spatial modeling with Ordinary Kriging based on 47 drilling data points. The findings show that Seam C coal has an average ash content of 6.60 %, total sulfur of 0.70 %, moisture of 12.14 %, and a calorific value of 6324.74 kcal/kg. Petrographic analysis reveals a dominance of vitrinite maceral with vitrinite reflectance between 0.44-0.46 %, while coal facies analysis indicates that most samples from the WBS, LMH, and AKA sites formed in an Upper Delta Plain environment with telmatic to wet forest swamp facies. Meanwhile, the BA1 site developed in a Lower Delta Plain environment with marsh facies, influenced by a higher influx of clastic sediments. Spatial analysis shows increased ash and sulfur levels in the northern part of the study area, while calorific value tends to be higher in the southwest. The results suggest that variations in Seam C coal quality are mainly controlled by changes in depositional facies, while the degree of coalification remains relatively uniform across the study area. The novelty of this research lies in its integrated approach, combining petrographic analysis, coal facies, coal quality, and geostatistics to explore the relationship between depositional environment and the spatial distribution of coal quality in the Sinamar Formation. This method offers a more complete understanding of the geological factors influencing coal quality and can support resource evaluation and coal exploration planning in the Sinamar Formation and other coal basins with similar features.

Keywords: Coal, Depositional Environment, Coal Facies, Coal Quality, Coal Petrography, Ordinary Kriging.

1. Introduction

Coal is one of the energy resources that plays a crucial role in supporting energy security and economic development in Indonesia. Although the transition to low-carbon energy continues to progress, coal remains the primary energy source for power plants and various industrial sectors due to its abundant availability and high economic value. Indonesia is one of the world's largest coal producers, with reserves concentrated primarily on the islands of Sumatra and Kalimantan (IEA, 2024; Kementerian ESDM, 2024). The formation of coal deposits is influenced by the interaction between paleoclimate conditions, the tectonic evolution of sedimentary basins, and the depositional environment, which controls the accumulation and preservation of organic material (Dai et al., 2020; Jamaluddin et al., 2025). Differences in these factors result in variations in coal quality that directly affect its economic value, mining strategies, and potential uses (Asiwaju et al., 2024; Dai et al., 2020; Hibatullah et al., 2026).

Coal quality is determined by parameters such as ash content, sulfur content, moisture content, volatile matter, fixed carbon, and calorific value. Variations in these parameters are influenced by the peat formation process, the degree of coalification, and the environmental conditions during deposition. An increase in clastic material input tends to raise ash content, while the influence of marine or brackish water environments can increase sulfur content, thereby reducing coal quality (Dai et al., 2020; Karyadi and Setiawan, 2023; Monita et al., 2021; Qadaryati et al., 2023). In addition, hydrological conditions, the type of vegetation that forms peat, and paleoclimate also influence the petrographic characteristics and quality of coal (Asiwaju et al., 2024; Biswas et al., 2024). Therefore, an understanding of the relationship between the depositional environment and coal quality is important for supporting exploration, resource evaluation, and mining planning (Hibatullah et al., 2026; Idarwati and Maulia, 2024; Tang et al., 2020).

Interpretation of coal deposition environments is currently often carried out through the integration of petrographic analysis and coal facies analysis using the Tissue Preservation Index (TPI), Gelification Index (GI), Vegetation Index (VI), and Groundwater Index (GWI). This approach allows for the reconstruction of the vegetation types that formed the peat, the hydrological conditions, and the evolution of ancient swamp environments. Several studies have shown that petrographic characteristics and depositional environments influence coal quality, both in the Muara Enim Formation (Monita et al., 2021; Rahmad et al., 2022), the Sawahlunto Formation (Patria and Anggara, 2022), and in coal basins outside Indonesia (Biswas et al., 2024; Zamani et al., 2023). Furthermore, advances in statistical and geostatistical analysis have enabled a more quantitative evaluation of the spatial distribution of coal quality (Niedoba et al., 2020).

The study area is located in the Leban region, Muaro Bungo Regency, Jambi Province, which geologically belongs to the Oligocene-aged Sinamar Formation in the northwestern part of the South Sumatra Basin (Zajuli and Panggabean, 2014, 2013). This formation consists of sandstone, mudstone, shale, and coal beds that exhibit variations in quality both laterally and vertically (Hibatullah et al., 2026; Rizky et al., 2023). Previous research on the Sinamar Formation has generally focused on the sedimentology of fine-grained clastic rocks and the potential of hydrocarbon source rocks, whereas studies on the petrographic characteristics of coal and their relationship to coal quality remain very limited.

To date, there has been no comprehensive study that integrates petrographic analysis, coal facies analysis (TPI, GI, VI, and GWI), coal quality analysis, and geostatistical modeling to explain the geological control over the spatial distribution of coal quality in the Sinamar Formation, particularly in the Leban area. This research gap highlights the need for an integrated approach to gain a more comprehensive understanding of the relationship between the depositional environment, petrographic characteristics, and coal quality distribution.

This study integrates coal petrographic analysis, coal facies analysis using the TPI, GI, VI, and GWI indices, coal quality analysis (proximate and ultimate), and geostatistical modeling using the Ordinary Kriging method to evaluate the relationship between the depositional environment and the spatial distribution of coal quality in the Sinamar Formation. This approach is expected to provide a more comprehensive understanding of the geological factors that control variations in coal quality, while also providing information to support exploration, resource evaluation, and mining planning.

Based on the above description, this study aims to interpret the characteristics of the Seam C depositional environment based on petrographic and coal facies analyses, evaluate the relationship between petrographic characteristics, coal facies, and coal quality, and analyze the spatial distribution of coal quality based on geostatistical analysis and its relationship with the depositional environment. To achieve this objective, this study employs an integrated approach that combines petrographic analysis, coal facies analysis, coal quality analysis, and geostatistical modeling to explain the influence of the depositional environment on variations in coal quality in Seam C of the Sinamar Formation.

2. Regional Geology

Regionally, the study area is located in the northwestern part of the South Sumatra Basin and falls within the Painan and Northeastern Muara Siberut Geological Map Sheets (Rosidi et al., 1996). Based on regional geological maps, the study area is dominated by the Oligocene-aged Sinamar Formation, which is the primary coal-bearing unit in the study area. This formation was deposited on top of Pre-Tertiary to Jurassic granite bedrock, and is subsequently overlain conformably by the Miocene Rantauikil Formation and unconformably by the Pliocene-Pleistocene Kasai Formation (Rosidi et al., 1996). Lithologically, the Sinamar Formation consists of an interbedding of conglomerate, sandstone, mudstone, claystone, shale, and coal layers that reflect a fluvial-delta plain depositional system, making it one of the major coal-bearing formations in the northwestern part of the South Sumatra Basin (Zajuli and Panggabean, 2014, 2013).

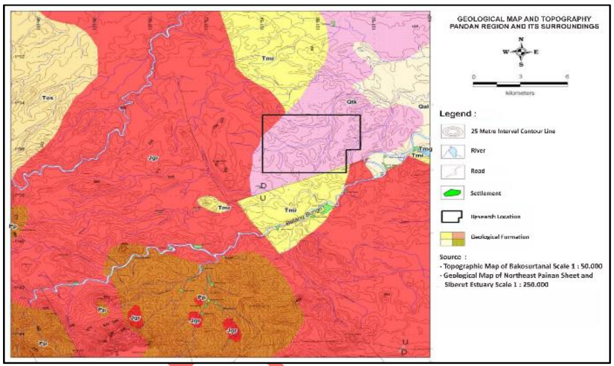

Fig. 1. Modified regional geological map of the study area (Rosidi et al., 1996)

Regional stratigraphy indicates that the Sinamar Formation consists of an alternation of sandstone, shale, claystone, and coal seams, namely Seam A, Seam B, and Seam C, with Seam C being the primary coal seam in the study area. This lithological variation indicates the presence of recurring sedimentation cycles in fluvial to delta plain environments, which facilitated the development of peat-forming swamps. The Sinamar Formation is part of the filling of the South Sumatra Basin during the Tertiary period, when the creation of accommodational space due to basin subsidence allowed for the accumulation of clastic sediments and the development of coal-forming swamp environments (Hibatullah et al., 2026). The clastic materials that make up the Sinamar Formation are believed to have originated from the Pre-Tertiary highlands and the Barisan Mountains in the west, which were transported via fluvial systems to the deltaic plain, thereby influencing the distribution of sedimentary facies, the thickness of coal seams, and variations in coal quality (Hibatullah et al., 2026; Patria and Anggara, 2022).

Regionally, the characteristics of the Sinamar Formation show similarities to other coal-bearing formations in Sumatra. A study by Monita et al. (2021) on the Muara Enim Formation showed that environmental changes from the upper delta plain to the lower delta plain led to an increase in ash content and a decline in coal quality. Similar results were also reported by Patria and Anggara (2022) for the Sawahlunto Formation, indicating that a swamp environment with a low supply of clastic sediments results in a predominance of vitrinite and higher coal quality. In addition, Qadaryati et al. (2023) showed that the increasing influence of the lower delta plain is associated with rising sulfur and mineral matter content, while Asiwaju et al. (2024) emphasized that the hydrological conditions of the swamp and sediment supply are the primary factors controlling variations in coal quality. This regional geological framework serves as the basis for interpreting the depositional environment and variations in the quality of Seam C coal in this study.

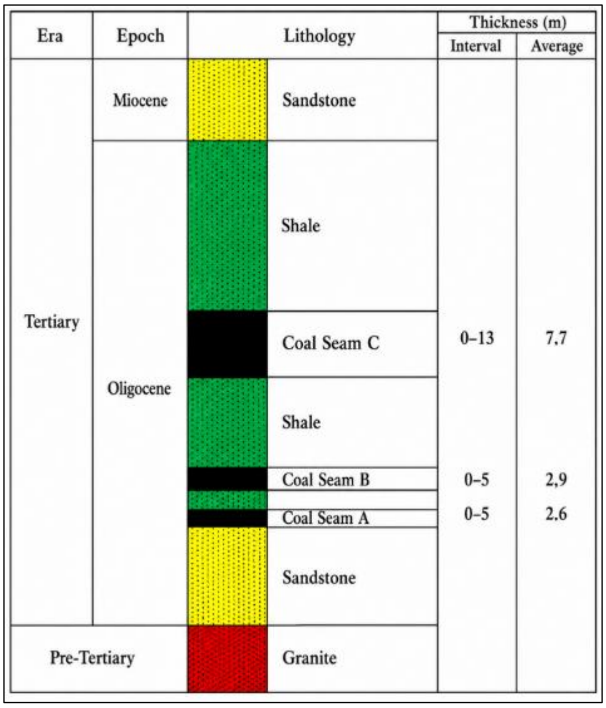

Fig 2. Regional stratigraphic column of the Sinamar Formation showing the lithological sequence and the locations of Seam A, Seam B, and Seam C

3. Research Methodology

3.1 Research Location

The study site is located in the Leban area and its surroundings, which administratively fall under the Rantau Pandan Subdistrict, Muaro Bungo Regency, Jambi Province, Indonesia. Geographically, the study area is situated at coordinates between 1°34'30"-1°37'00" S and 101°54'00"-101°57'30" E. The study area is part of the Sinamar Formation, which contains Seam C as the primary object of the study.

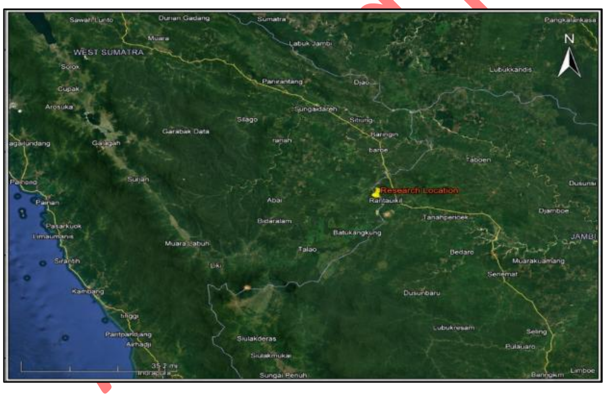

Fig 3. Map of the study site

3.2 Research Methods and Types of Research Data

This study employs a quantitative approach that integrates coal quality analysis, coal petrography, coal facies interpretation, descriptive statistical analysis, and geostatistical analysis to evaluate the relationship between the depositional environment and the spatial distribution of coal quality in Seam C.

Primary data were obtained from 12-channel samples collected at four outcrop locations along Seam C, with three channel samples at each location. Sampling was conducted perpendicular to the coal stratification plane, starting from the roof and extending to the floor of the seam, so that the entire thickness of the seam would be represented. Samples were collected continuously from fresh coal sections, avoiding areas that had undergone weathering, oxidation, or contamination by foreign materials. The four locations were selected to represent the lateral variation of Seam C based on the distribution of outcrops, seam continuity, and the geological conditions of the study area.

All samples were analyzed using proximate, ultimate, and petrographic analyses. Proximate analysis was used to determine total moisture, ash, volatile matter, and fixed carbon, while ultimate analysis was used to determine the content of carbon, hydrogen, nitrogen, sulfur, and oxygen. Petrographic analysis was conducted to determine the maceration composition and vitrinite reflectance as a basis for interpreting the characteristics of the organic material and the coal-forming environment.

The secondary data consists of 47 exploratory drill holes containing information on the thickness of Seam C, ash content, total sulfur, total moisture, and calorific value, and is supported by regional geological maps, stratigraphic data, and relevant scientific literature. All drilling sites were used because they provided comprehensive coal quality parameters and were distributed throughout the study area, thereby providing adequate spatial coverage to represent variations in coal quality and to support statistical analysis and geostatistical modeling.

Table 1. Types and sources of research data

Data Types	Amount of Data	Parameters Analyzed	Methods of Analysis
Coal sample	12 samples	Total Moisture, Ash, Volatile Matter, Fixed Carbon	Analisis Proksimat
Coal sample	12 samples	Carbon, Hydrogen, Nitrogen, Sulphur, Oxygen	Analisis Ultimat
Coal sample	12 samples	Maseral composition and vitrinite reflectance	Analisis Petrografi
Petrographic data	12 samples	Tissue Preservation Index (TPI), Gelification Index (GI), Vegetation Index (VI), Groundwater Index (GWI)	Diagram Diessel (1986) dan Calder et al. (1991)
Exploratory drilling data	47 points	Seam C Thickness, Total Moisture, Ash, Total Sulphur, Calorific Value	Statistik Deskriptif dan Ordinary Kriging

3.3 Data Processing and Analysis Techniques

Data from proximate, ultimate, and petrographic analyses were used to evaluate the quality characteristics of the coal and to interpret the depositional environment of Seam C. Descriptive statistical analysis was performed on the parameters of seam thickness, total moisture, ash, total sulfur, and calorific value by calculating the minimum, maximum, mean, median, standard deviation, and skewness to describe the distribution characteristics of each coal quality parameter.

Petrographic data, including maceral composition and vitrinite reflectance, were used to calculate the Tissue Preservation Index (TPI) and Gelification Index (GI) according to Diessel (1986), as well as the Groundwater Index (GWI) and Vegetation Index (VI) according to Calder et al. (1991). These values were then plotted on coal facies and paleomire diagrams to interpret the degree of plant tissue preservation, gelification intensity, vegetation type, hydrological conditions, and the depositional environment.

The Tissue Preservation Index (TPI) was calculated using the following equation:

$$TPI = \frac{TV+TI}{DV+GV+DI+GIn} \quad (1)$$

The Gelification Index (GI) was calculated using the following equation:

$$GI = \frac{V+GIn}{TI+DI} \quad (2)$$

where TV = Telovitrinite, DV = Detrovitrinite, GV = Gelovitrinite, V = Total Vitrinite, TI = Teloinertinite, DI = Detroinertinite, and GIn = Geloinertinite.

The Groundwater Index (GWI) was calculated using the following equation:

$$GWI = \frac{CG+MM}{T+TC+DV} \quad (3)$$

The Vegetation Index (VI) was calculated using the following equation:

$$VI = \frac{TV+F+SF+Su+R}{DV+ID+LD+Sp+Ct+Ag} \quad (4)$$

where CG = Corpogelinite, MM = Mineral Matter, T = Textinite, TC = Telocollinite, F = Fusinite, SF = Semifusinite, Su = Suberinite, R = Resinite, ID = Inertodetrinite, LD = Liptodetrinite, Sp = Sporinite, Ct = Cutinite, Ag = Alginite.

Geostatistical analysis was performed using the Ordinary Kriging method with the aid of Stanford Geostatistical Modeling Software (SGeMS), while the interpolation results were visualized using Surfer software. Before interpolation, an experimental variogram analysis was conducted to evaluate the spatial continuity of each coal quality parameter as a basis for applying Ordinary Kriging. This method was chosen because it produces unbiased estimates while accounting for the spatial continuity of the data. Interpolation was performed on the parameters of seam thickness, ash content, total sulfur, total moisture, and calorific value to generate maps of the spatial distribution of coal quality. The interpolation results were then integrated with statistical analysis, petrographic characteristics, and coal facies interpretation to evaluate the relationship between the depositional environment and spatial variations in the quality of Seam C coal.

4. Results and Discussion

4.1 Coal Quality Characteristics of Seam C

The quality characteristics of Seam C coal were evaluated through proximate, ultimate, and petrographic analyses to identify variations in coal quality and the geological factors that control its formation. Proximate analysis is used to evaluate key coal quality parameters; ultimate analysis is used to determine the elemental composition of coal; and petrographic analysis is used to identify the macerals, mineral matter content, and vitrinite reflectance as a basis for interpreting the depositional environment. The integration of these three analyses provides insight into the relationship between the characteristics of organic matter, the depositional environment, and variations in coal quality (Asiwaju et al., 2024; Biswas et al., 2024; Dai et al., 2020; Monita et al., 2021; Patricia et al., 2020).

4.1.1 Proximate Analysis

The results of the proximate analysis of Seam C coal are presented in Table 2.

Table 2. Proximate analysis results of Seam C coal samples showing Total Moisture (TM), Inherent Moisture (IM), Calorific Value (CV), Volatile Matter (VM), Fixed Carbon (FC), And Ash Content (Ash).

ID Sample	Proximate Analysis					
	TM %ar	IM %adb	CV %adb	VM %adb	FC %adb	ASH %adb
WBS-1	17.65	12.17	6151	34.10	49.53	4.21
WBS-2	15.81	14.82	5689	32.60	47.94	4.65
WBS-3	18.29	12.12	5580	34.25	46.80	6.84
LMH-1	16.02	11.72	5769	35.30	48.36	4.61
LMH-2	24.06	13.15	5836	34.76	48.19	3.90
LMH-3	21.52	11.91	5317	35.50	45.97	6.63
AKA-1	20.71	12.68	6143	36.54	46.04	4.74
AKA-2	23.09	12.21	6219	36.24	47.30	4.25
AKA-3	18.9	12.69	5995	37.04	44.39	5.88
BA1-1	24.7	8.6	5100	35.71	40.28	15.41
BA1-2	16.28	9.1	5159	36.20	44.70	10.00
BA1-3	19.4	13.15	5139	32.65	42.30	11.90

Based on the results of the proximate analysis, Seam C coal has a total moisture content of 15.81-24.70 %, ash content of 3.90-15.41 %, volatile matter of 32.60-37.04 %, fixed carbon of 40.28-49.53 %, and a calorific value of 5,100–6,219 kcal/kg (adb), which represent the principal parameters commonly used to evaluate coal quality and rank (Nefia and Manek, 2026). The greatest variation was observed in ash content and calorific value, while volatile matter showed a relatively narrow range, indicating a relatively uniform degree of coalification (Mardhiyah et al., 2024; Tang et al., 2020).

Samples from the WBS, LMH, and AKA sites had lower ash content and higher calorific values than BA1, which had the highest ash content (15.41 %) and the lowest calorific value (5,100 kcal/kg). The negative correlation between ash content and calorific value suggests that an increase in mineral matter content, resulting from the supply of clastic sediments during peat formation, leads to a decline in coal quality. This suggests that variations in the quality of Seam C are more strongly influenced by changes in the depositional environment than by differences in the degree of coalification, as also reported by Dai et al. (2020) and Monita et al. (2021).

4.1.2 Ultimate Analysis

The results of the ultimate analysis of Seam C coal are presented in Table 3.

Table 3. Ultimate analysis results of Seam C coal samples showing elemental Carbon (C), Hydrogen (H), Nitrogen (N), Oxygen (O), and Sulfur (S) contents.

ID Sample	Ultimate analysis				
	C % adb	H % adb	N % adb	O % adb	S %adb
WBS-1	71.14	5.78	0.88	21.52	0.68
WBS-2	69.14	5.72	0.71	23.87	0.56
WBS-3	67.93	5.33	0.98	24.91	0.85
LMH-1	68.33	5.56	1.48	24.11	0.52
LMH-2	70.56	5.67	1.49	21.77	0.47
LMH-3	68.78	5.45	1.57	23.57	0.51
AKA-1	66.11	5.21	1.74	26.34	0.63
AKA-2	66.23	5.41	1.49	26.14	0.61
AKA-3	65.45	5.11	0.23	26.78	0.73
BA1-1	52.22	4.61	2.06	39.87	2.43
BA1-2	53.11	4.67	1.8	39.67	0.75
BA1-3	55.26	4.97	1.32	37.21	1.24

The carbon content of Seam C coal ranges from 52.22-71.14 %, hydrogen from 4.61-5.78 %, nitrogen from 0.23-2.06 %, oxygen from 21.52-39.87 %, and sulfur from 0.47-2.43 %. The highest carbon content was found at the WBS site, while the highest oxygen and sulfur contents were found at BA1.

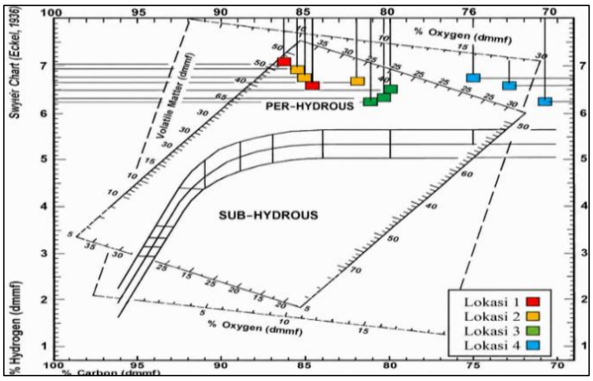

Fig 4. Classification of Seam C coal samples based on the Seyler Chart (Eckel, 1936), illustrating the relationship between hydrogen and oxygen contents of the analyzed samples.

Based on Fig. 4, all samples fall within the per-hydrous zone according to Seyler's classification (Eckel, 1936), indicating humic-type organic material with a relatively uniform degree of carbonization. However, the BA1 sample exhibited higher oxygen and sulfur content, consistent with increased ash content and decreased calorific value. This pattern indicates that coal quality is more strongly influenced by hydrological conditions and sediment supply during peat formation than by variations in the degree of coalification, consistent with the findings of Qadaryati et al. (2023) and Asiwaju et al. (2024).

4.1.3 Petrographic Characteristics

The petrographic characteristics of Seam C coal are presented in Table 4, while the distribution of maceral composition is shown in Fig. 5.

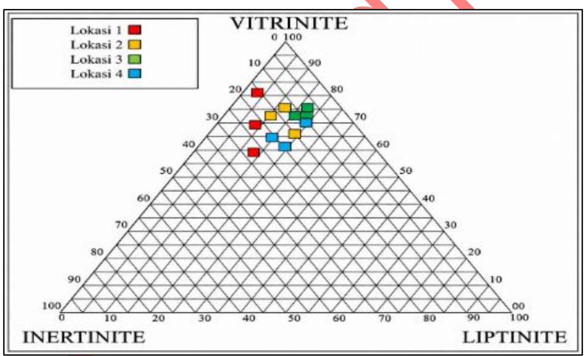

Fig 5. Triangular maceral composition diagram showing the relative proportions of vitrinite, liptinite, and inertinite in Seam C coal samples.

Table 4. Average maceral composition and vitrinite reflectance of Seam C coal from the four sampling locations.

Location	Vitrinite (%)	Liptinit (%)	Inertinit (%)	Mineral Matter (%)	Rv (%)
WBS	74.4	15.6	7.3	2.7	0.46
LMH	76.4	8.3	4.3	10.9	0.44
AKA	79.7	7.6	6.2	6.4	0.46
BA1	65.7	6.3	4.5	23.5	0.46

Coal Seam C is dominated by vitrinite, with an average of 74.1 ± 7.5 %, while liptinite and inertinite account for 9.5 ± 4.9 % and 5.6 ± 2.7 %, respectively. The vitrinite reflectance value is relatively uniform (0.46 ± 0.01 %), indicating that all samples have nearly the same level of organic maturity (Nefia and Manek, 2026; Rahmad et al., 2022).

The predominance of vitrinite indicates that the coal formed primarily from woody vegetation preserved under reducing swamp conditions, while the high mineral matter content in BA1 suggests an increased supply of clastic sediments during peat formation. This interpretation is consistent with the results of proximate and ultimate analyses, which indicate higher ash and sulfur contents and a lower calorific value at that location. These results support the interpretation that variations in the quality of Seam C coal are primarily controlled by the depositional environment, whereas the degree of coalification is relatively uniform, as also reported by Monita et al. (2021) and Patria and Anggara (2022).

4.2 Depositional Environment Interpretation

The interpretation of the depositional environment was conducted by integrating the results of petrographic analysis with the Tissue Preservation Index (TPI), Gelification Index (GI), Vegetation Index (VI), and Groundwater Index (GWI). The TPI-GI index is used to evaluate the degree of plant tissue preservation and the intensity of gelation during peat formation based on the classification of Diessel (1986), while the VI-GWI index is used to reconstruct paleomire characteristics based on vegetation type and hydrological conditions according to Calder et al. (1991) and has been widely applied in recent coal facies studies (Dai et al., 2020; Jamaluddin et al., 2025; Mangs et al., 2022).

4.2.1 Coal Facies Interpretation Based on TPI–GI

The Tissue Preservation Index (TPI) and Gelification Index (GI) values obtained from the petrographic analysis are presented in Table 5, while the results plotted on the Diessel (1986) coal facies diagram are shown in Fig. 6-9.

Table 5. Tissue Preservation Index (TPI) and Gelification Index (GI) values of Seam C coal samples used for depositional environment interpretation.

Sampel	Location	TPI	GI
WBS-1		3.28	9.84
WBS-2	1	3.57	23.38
WBS-3		3.51	5.94
LMH-1		1.53	17.65
LMH-2	2	1.53	15.13
LMH-3		2.01	20.60
AKA-1		1.48	21.91
AKA-2	3	1.52	13.27
AKA-3		1.61	8.75
BA1-1	4	0.13	67
BA1-2		0.36	13.6

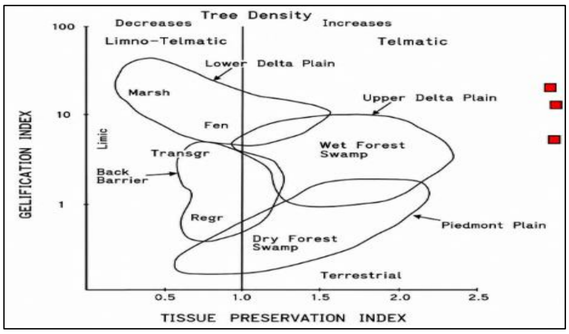

Fig 6. TPI-GI relationship diagram for Seam C coal samples at the WBS site based on Diessel (1986) coal facies classification.

Based on Fig. 6, all samples from the WBS site are classified as belonging to the Upper Delta Plain facies.

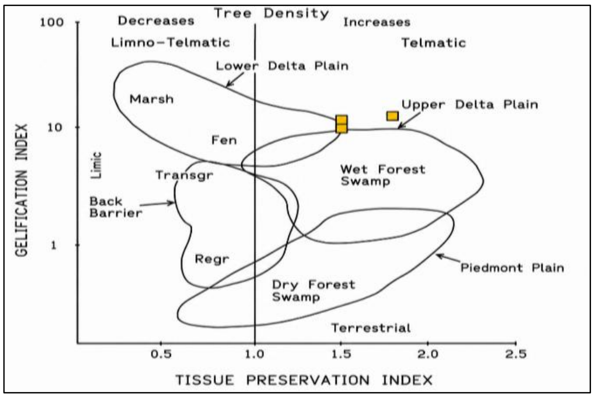

Fig 7. TPI-GI relationship diagram for Seam C coal samples at the LMH site based on Diessel (1986) coal facies classification.

Most of the samples at the LMH site also belong to the Upper Delta Plain facies.

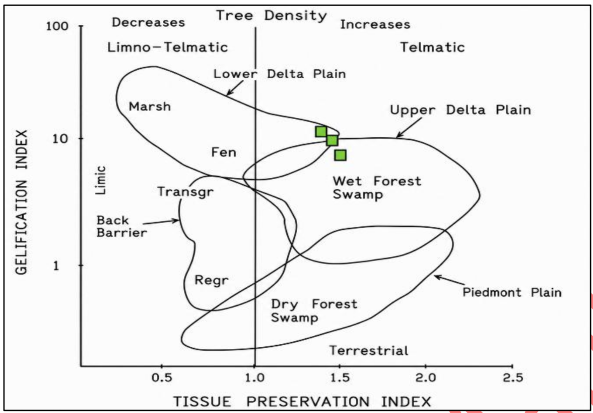

Fig 8. TPI-GI relationship diagram for Seam C coal samples at the AKA site based on Diessel (1986) coal facies classification.

All samples from the AKA site exhibit the characteristics of the Upper Delta Plain facies.

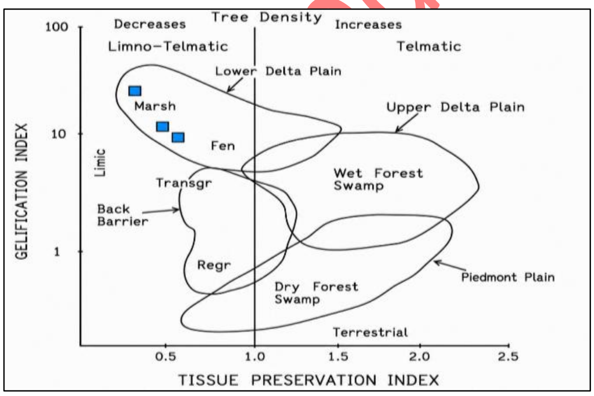

Fig 9. TPI-GI relationship diagram for Seam C coal samples at location BA1 based on Diessel (1986) coal facies classification.

Unlike other locations, the sample at BA1 is found in the Marsh facies.

The results of the TPI-GI analysis show that most samples from WBS, LMH, and AKA developed in the Upper Delta Plain facies, while BA1 shows a facies change to Marsh. The relatively high TPI values for WBS, LMH, and AKA indicate good preservation of plant tissue, while the high GI values indicate that gelification occurred intensively in a water-saturated marsh environment. These conditions are consistent with the predominance of vitrinite, low mineral matter content, low ash content, and a relatively high calorific value, indicating that the peat formed in an environment with a limited supply of clastic sediments (Diessel, 1986; Mangs et al., 2022).

In contrast, the BA1 site showed low TPI values with consistently high GI values, indicating that the plant tissue underwent more intensive degradation before burial, even though the gelation process was still ongoing under flooded marsh conditions. These conditions are interpreted as a marsh environment more strongly influenced by periodic flooding and clastic sediment input. This interpretation is supported by the high mineral matter, ash, and sulfur content, as well as the low calorific value at the BA1 site (Panda et al., 2022). Thus, differences in depositional facies are the primary factors controlling variations in the quality of Seam C coal, while the degree of coalification is relatively uniform, as indicated by the vitrinite reflectance values. These results were then verified using VI-GWI analysis to obtain a more comprehensive paleomire reconstruction (Biswas et al., 2024; Petersen et al., 2022).

4.2.2 Paleomire Interpretation Based on VI-GWI

The Vegetation Index (VI) and Groundwater Index (GWI) values obtained from the petrographic analysis are presented in Table 6, while the results plotted on the paleomire diagram by Calder et al. (1991) are shown in Fig. 10-13.

Table 6. Vegetation Index (VI) and Groundwater Index (GWI) values of Seam C coal samples were used to evaluate peat-forming vegetation and hydrological conditions.

Sampel	Location	GWI	VI
WBS-1		0.11	3.74
WBS-2	1	0.02	2.57
WBS-3		0.11	3.31
LMH-1		0.08	1.75
LMH-2	2	0.29	1.77
LMH-3		0.13	2.01
AKA-1		0.19	1.82
AKA-2	3	0.09	1.68
AKA-3		0.11	1.67
BA1-1	4	0.44	0.17
BA1-2		0.23	0.44

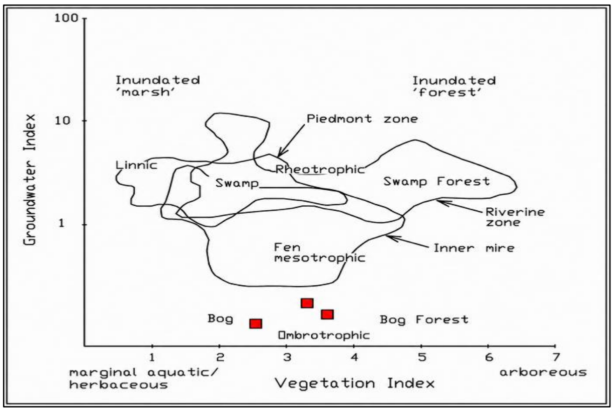

Fig 10. A relationship diagram showing the Vegetation Index (VI) and Groundwater Index (GWI) for coal samples from Seam C at the WBS site, based on the paleomire classification by Calder et al. (1991).

All samples at the WBS site are located in the Bog-Ombrotrophic zone.

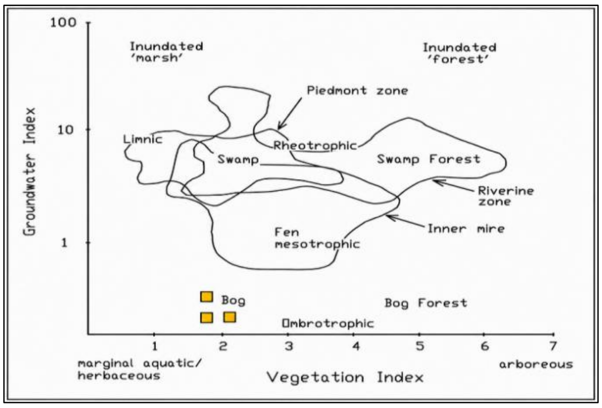

Fig 11. A relationship diagram showing the Vegetation Index (VI) and Groundwater Index (GWI) for coal samples from Seam C at the LMH site, based on the paleomire classification by Calder et al. (1991).

All samples from the LMH site also fell within the Bog-Ombrotrophic category.

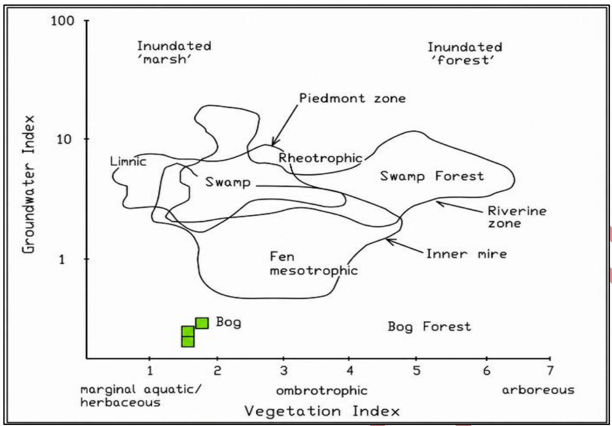

Fig 12. A relationship diagram showing the Vegetation Index (VI) and Groundwater Index (GWI) for coal samples from Seam C at the AKA site, based on the paleomire classification by Calder et al. (1991).

All samples at the AKA site exhibited bog-ombrotrophic characteristics.

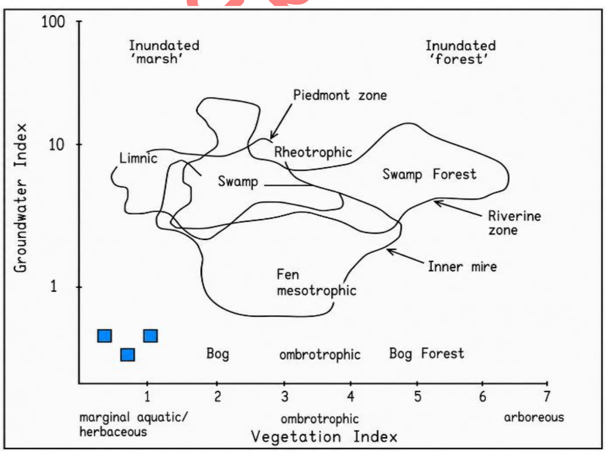

Fig 13. A relationship diagram showing the Vegetation Index (VI) and Groundwater Index (GWI) for coal samples from Seam C at location BA1, based on the paleomire classification by Calder et al. (1991).

The sample from location BA1 remains within the Bog-Ombrotrophic zone, but has a higher GWI value and a lower VI value than the other locations.

Based on the VI and GWI values and the samples' positions on the paleomire diagram by Calder et al. (1991), all samples from Seam C developed in a bog-ombrotrophic environment. The relatively high VI values at the WBS, LMH, and AKA sites indicate that the peat is dominated by arboreal vegetation, while the low GWI values suggest that peat formation occurred under relatively stable hydrological conditions with a water supply dominated by rainfall. This interpretation is consistent with the predominance of vitrinite and the low mineral matter content, which indicate that organic material was well preserved during peat accumulation (Mangs et al., 2022; Monita et al., 2021).

Although it belongs to the same paleomire type, the BA1 site exhibits a higher GWI value and a lower VI value compared to the other sites. These conditions indicate an increased influence of groundwater and clastic sediment supply during peat formation, which in turn led to an increase in mineral matter content, ash content, and sulfur content, as well as a decrease in calorific value. These results are consistent with the TPI-GI interpretation, which classifies BA1 as a Marsh facies, suggesting that the observed changes reflect variations in local hydrological conditions rather than changes in the vegetation types that make up the peat (Idarwati and Maulia, 2024; Panda et al., 2022; Rahmad et al., 2022).

Overall, the VI-GWI diagram complements the results of the TPI-GI interpretation. The TPI-GI diagram emphasizes peat-forming facies based on plant tissue preservation and gelification intensity, while the VI-GWI provides information on the type of vegetation that formed the peat and the hydrological conditions. The integration of these two approaches indicates that Seam C generally formed in a bog–ombrotrophic environment in the Upper Delta Plain, with a local transition to a marsh facies at location BA1 due to increased groundwater influence and clastic sediment input (Hibatullah et al., 2026; Mangs et al., 2022).

4.2.3 Integrated Interpretation of Depositional Environment

Table 7. Vegetation Index (VI) and Groundwater Index (GWI) values of Seam C coal samples were used to evaluate peat-forming vegetation and hydrological conditions.

Sample	Coal Facies	Depositional Environment	Coal Quality
WBS	Telmatic Swamp	Upper Delta Plain	High
LMH	Telmatic Swa mp	Upper Delta Plain	High
AKA	Wet Forest Swamp	Upper Delta Plain	High
BA1	Marsh	Lower Delta Plain	Moderate

An integration of the results of petrographic analysis, coal facies indices (TPI-GI and VI-GWI), and coal quality parameters indicates that the depositional environment is the primary factor controlling variations in the quality of Seam C coal Table 7. The WBS, LMH, and AKA sites consistently exhibit characteristics of an Upper Delta Plain environment with facies ranging from Telmatic Swamp to Wet Forest Swamp. This environment is characterized by the dominance of vitrinite as the major component, good preservation of plant tissue, intensive gelification, and a relatively low supply of clastic sediments. These conditions support the formation of coal with low ash and sulfur content and a relatively high calorific value (Asiwaju et al., 2024; Dai et al., 2020; Hibatullah et al., 2026; Mangs et al., 2022; Monita et al., 2021).

In contrast, the BA1 site indicates a facies change to a marsh that developed within the Lower Delta Plain system. This environment was influenced by more dynamic hydrological conditions and a greater influx of clastic sediments, which increased the mineral matter content, ash content, and sulfur content, and reduced the coal's calorific value. Although all samples showed relatively uniform levels of coalification based on vitrinite reflectance values, differences in depositional conditions resulted in significant variations in coal quality among locations (Panda et al., 2022; Qadaryati et al., 2023; Rahmad et al., 2022).

The results of this study are consistent with those of Monita et al. (2021) on the Muara Enim Formation and Patria and Anggara (2022) on the Sawahlunto Formation, which show that coal formed in an Upper Delta Plain environment generally has a higher vitrinite content and better quality than coal that developed in environments with greater clastic sediment influence. However, in the Sinamar Formation's Seam C, the transition to the Lower Delta Plain environment occurred only locally at site BA1. This suggests that variations in coal quality are influenced more by changes in depositional facies on a local scale than by regional changes (Hibatullah et al., 2026).

Overall, the integration of petrographic analysis, coal facies indices, and coal quality parameters indicates that changes in the depositional environment control the distribution of quality in Seam C through variations in the preservation of organic matter, hydrological conditions, and the intensity of clastic sediment input. Thus, this integrated approach provides a stronger basis for interpretation than the use of a single parameter in isolation, while also serving as a foundation for explaining the spatial distribution patterns of coal quality in the subsequent geostatistical discussion (Petersen et al., 2022; Tang et al., 2020).

4.3 Statistical and Geostatistical Analysis of Coal Quality Distribution

To evaluate the variation in the quality of Seam C coal across the study area, a descriptive statistical analysis was conducted on 47 drilling data points, including seam thickness, ash content, total sulfur, total moisture, and calorific value. This analysis aimed to describe the distribution characteristics of each parameter prior to spatial modeling using the Ordinary Kriging method. The integration of statistical and geostatistical analysis makes it possible to identify patterns in coal quality distribution and their relationship to geological conditions and the depositional environment.

4.3.1 Statistical Characteristics of Coal Quality

Based on Table 8, the thickness of Seam C ranges from 1.05 to 12.99 m, with an average of 8.51 m, while the coal quality shows considerable variation. Ash content ranges from 3.59-14.49 %, sulfur from 0.45-2.28 %, total moisture from 7.99-20.45%, and calorific value from 5340.40-6652.06 kcal/kg. The standard deviation values show that ash and sulfur content exhibit greater variation than other parameters, indicating that these two parameters are more influenced by local geological conditions than by changes in the degree of coalification (Asiwaju et al., 2024; Biswas et al., 2024; Niedoba et al., 2020).

Table 8. Descriptive statistics of Seam C coal quality parameters derived from 47 exploration drill holes.

Parameter	Min	Max	Average	SD	Skewness
Seam Thickness (m)	1.05	12.99	8.51	2.64	-0.97
Sulfur Content (%)	0.45	2.28	0.70	0.30	3.57
Ash Content (%)	3.59	14.49	6.60	2.48	1.41
Calorific Value (kcal/kg)	5340.40	6652.06	6324.74	265.07	-1.89
Moisture Content (%)	7.99	20.45	12.14	2.06	1.33

The skewness values indicate that the ash content (1.41), sulfur content (3.57), and total moisture (1.33) have positively skewed distributions, while seam thickness (-0.97) and calorific value (-1.89) show negatively skewed distributions. These distributions indicate that most of the study area has relatively good coal quality, while extreme values occur only at specific locations (Jeuken et al., 2020; Niedoba et al., 2020).

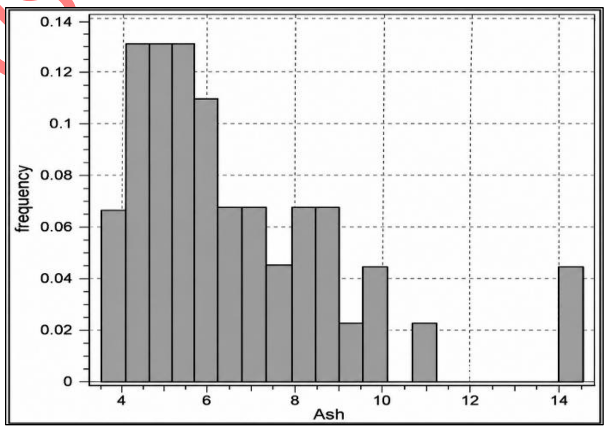

Fig 14. Histogram of the ash content distribution for Seam C.

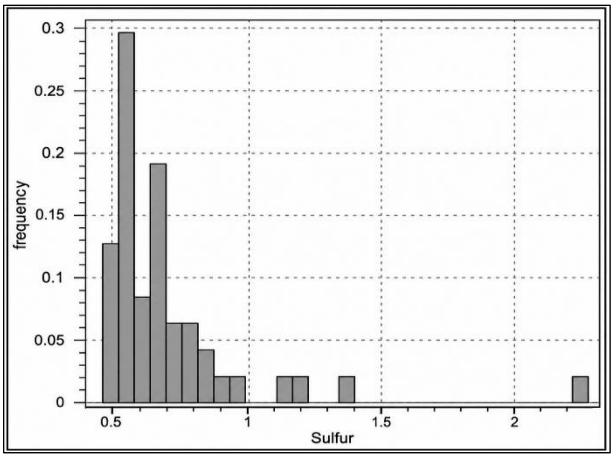

Fig 15. Histogram of the total sulfur distribution in Seam C.

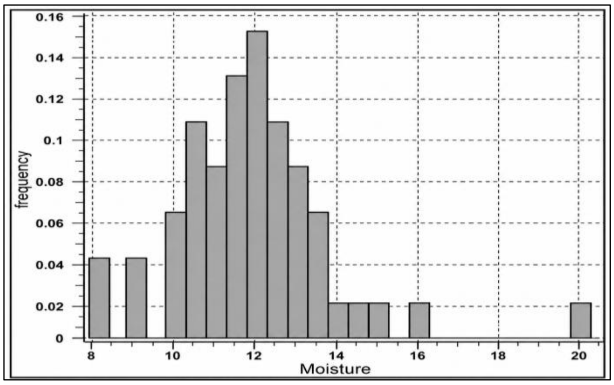

Fig 16. Histogram of the total moisture distribution for Seam C

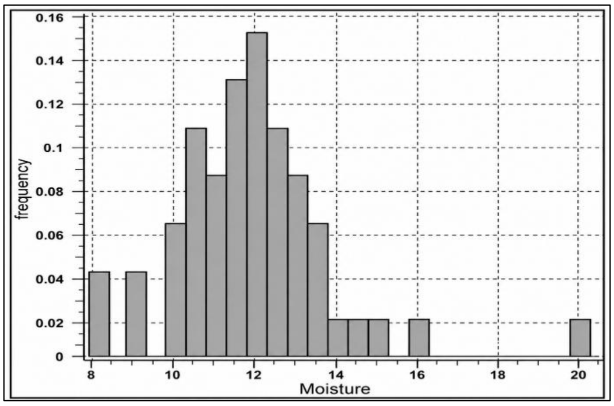

Fig 17. Histogram of the heat value distribution for Seam C.

The histograms in Fig. 14-17 show that the distributions of ash, sulfur, and total moisture content skew to the right, while the calorific value skews to the left. This pattern indicates that most of Seam C has relatively low ash, sulfur, and moisture content with a high calorific value, while quality anomalies occur only in a small number of locations. This distribution indicates that variations in coal quality are not random, but are controlled by local geological factors.

This interpretation is consistent with the results of petrographic and coal facies analyses, which indicate that WBS, LMH, and AKA formed in an Upper Delta Plain environment characterized by a predominance of vitrinite and low mineral matter content, whereas BA1 formed in a Lower Delta Plain-Marsh environment characterized by increasing mineral matter, ash, and sulfur content, as well as decreasing calorific value. Thus, the statistical distribution indicated by the skewness value reflects changes in the depositional environment, rather than differences in the degree of lithification, as is also indicated by the relatively uniform vitrinite reflectance values (Qadaryati et al., 2023; Rahmad et al., 2022).

These findings indicate that the statistical results do not stand alone but reinforce the petrographic and coal facies interpretations. Furthermore, geostatistical analysis was used to evaluate whether these statistical patterns also exhibit spatial continuity at the study area scale, thereby allowing for a more comprehensive explanation of the relationship between the depositional environment and coal quality distribution (Sideri et al., 2020).

4.3.2 Spatial Distribution of Coal Quality

The spatial distribution of coal quality in Seam C was modeled using the Ordinary Kriging method based on 47 exploratory drilling points. The interpolation results show that each coal quality parameter exhibits a systematic and interrelated distribution pattern, indicating that variations in coal quality are controlled by changes in the environmental conditions during the peat formation process (Dai et al., 2020; Sideri et al., 2020; Wulandari et al., 2020).

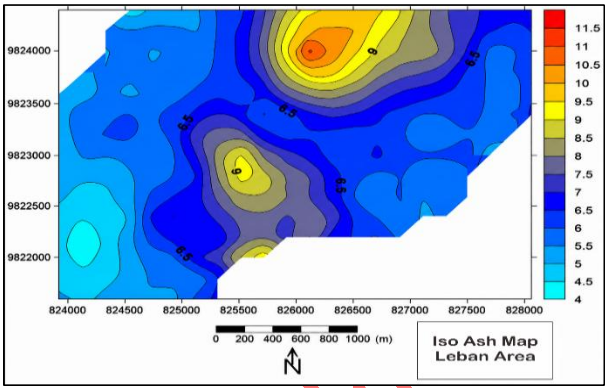

Fig 18. Spatial distribution of ash content of Seam C coal using Ordinary Kriging.

The distribution of ash content shows the highest concentrations in the northern part of the study area, while the southwestern part is dominated by lower ash content. This pattern indicates that the northern part receives a greater supply of clastic sediments, thereby increasing the mineral matter content of the coal.

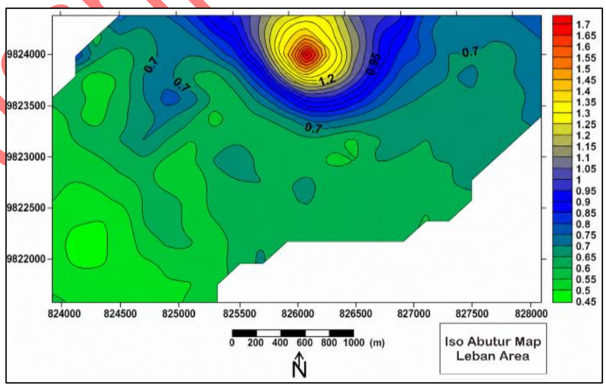

Fig 19. Spatial distribution of total sulfur of Seam C coal using Ordinary Kriging

The distribution of sulfur shows a pattern similar to that of ash content, with the highest concentrations occurring in the northern part, while most areas have sulfur content of less than 1 %. This pattern indicates that sulfur enrichment occurs in environments that are more heavily influenced by inorganic materials and are under reducing conditions.

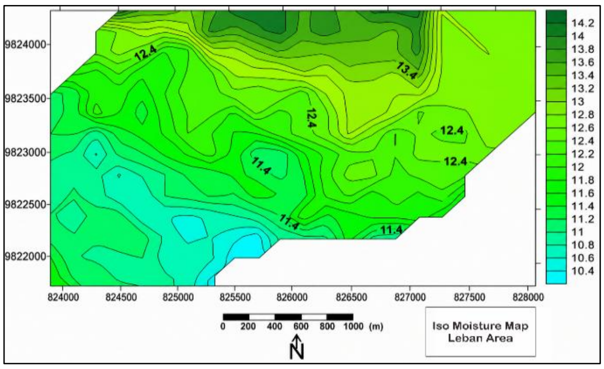

Fig 20. Spatial distribution of total moisture of Seam C coal using Ordinary Kriging.

The distribution of total moisture is relatively higher in the northern and eastern parts, while the southwestern part shows lower moisture content. These variations reflect differences in hydrological conditions and fluctuations in the groundwater table during peat formation.

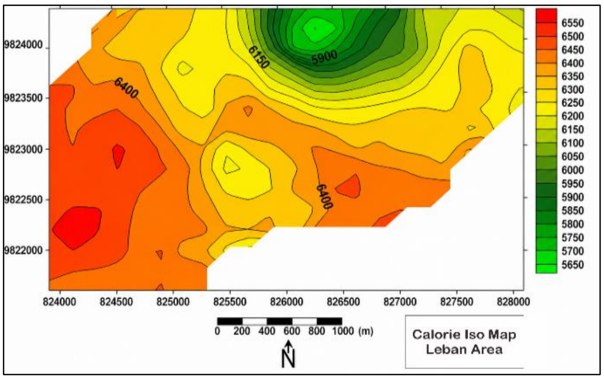

Fig 21. Spatial distribution of calorific value of Seam C coal using Ordinary Kriging

Conversely, the calorific value shows a pattern opposite to that of ash and sulfur content. The highest calorific values are found in the southwestern part, while the northern part has lower calorific values, indicating that an increase in mineral matter contributes to a decline in coal quality.

Overall, the interpolation results show consistent spatial relationships among the parameters. Zones with high ash, sulfur, and total moisture content are generally associated with lower calorific values, while areas with low ash and sulfur content have higher calorific values. This pattern indicates that coal quality is primarily controlled by the intensity of clastic sediment supply during peat formation (Asiwaju et al., 2024; Dai et al., 2020; Niedoba et al., 2020; Sideri et al., 2020).

This interpretation is consistent with the results of petrographic analysis, which indicate a predominance of vitrinite, as well as with the coal facies interpretation based on the TPI-GI and VI-GWI diagrams. Zones with low ash and sulfur content and high calorific value are associated with the Upper Delta Plain environment, while increased ash and sulfur content in the northern part indicate a transition toward the Lower Delta Plain-Marsh, which is influenced by a greater supply of sediment. Thus, the integration of geostatistical, petrographic, and coal facies results indicates that the depositional environment is the primary factor controlling the spatial distribution of coal quality in Seam C, whereas variations in coal rank do not have a significant influence on the observed quality distribution pattern (Hibatullah et al., 2026; Monita et al., 2021; Patria and Anggara, 2022; Rahmad et al., 2022).

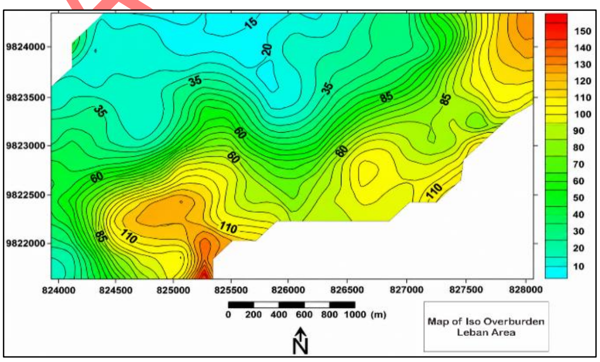

Fig 22. Spatial distribution of overburden thickness of Seam C using Ordinary Kriging.

The distribution of overburden thickness was also modeled using the Ordinary Kriging method. The interpolation results show that the overburden thickness varies from less than 20 m to more than 150 m, with relatively thin overburden in the north-northwest and increasing thickness toward the south. This pattern reflects variations in the geometry of the overburden layers above Seam C and the topographic conditions of the study area. Although important in the technical evaluation of mining operations, the distribution of overburden is not directly related to the intrinsic quality of the coal; therefore, in this study, it is used as supporting information regarding the geometric characteristics of the deposit (Hibatullah et al., 2026; Wulandari et al., 2020).

4.3.3 Geological Implications

The results of an integrated analysis of petrography, coal facies, coal quality, and geostatistical modeling indicate that the depositional environment is the primary factor controlling variations in the quality of Seam C coal, while the influence of the degree of coalification is relatively minor. This is indicated by the relatively uniform vitrinite reflectance values across all study sites, while the mineral matter, ash, and sulfur contents, as well as the calorific values, show consistent variations in response to changes in depositional facies (Asiwaju et al., 2024; Dai et al., 2020; Monita et al., 2021).

The coal at the WBS, LMH, and AKA sites is interpreted to have formed in an Upper Delta Plain environment with Telmatic Swamp-Wet Forest Swamp facies, characterized by a predominance of vitrinite, good preservation of organic matter, intensive gelification processes, and a relatively low supply of clastic sediments. These conditions resulted in coal with low ash and sulfur content and a relatively high calorific value. In contrast, the BA1 site shows a facies shift toward the Lower Delta Plain-Marsh, influenced by more dynamic hydrological conditions and a greater supply of clastic sediments, thereby increasing the content of mineral matter, ash, and sulfur and decreasing the coal's calorific value. This interpretation is supported by the results of Ordinary Kriging interpolation, which show that zones with high ash and sulfur content are spatially correlated with zones of low calorific value (Biswas et al., 2024; Qadaryati et al., 2023).

The results of this study are consistent with research on the Muara Enim Formation, which shows that changes in the depositional environment and coal facies have a greater influence on coal quality than the degree of coalification (Hibatullah et al., 2026; Monita et al., 2021; Rahmad et al., 2022). A similar pattern has also been reported in the Ombilin Basin (Patria and Anggara, 2022) as well as in several coal basins in Malaysia, South Africa, and Iran, indicating that hydrological conditions, the preservation of organic matter, and the supply of clastic sediments are the primary factors controlling coal quality (Asiwaju et al., 2024; Biswas et al., 2024; Zamani et al., 2023).

Although this study still has limitations-since the geostatistical analysis is based on 47 borehole points and is not yet supported by organic geochemical or sulfur isotope analyses-the consistency between the results of petrographic analysis, coal facies indices (TPI-GI and VI-GWI), coal quality, and geostatistical modeling indicates that the multidisciplinary approach used is capable of providing a comprehensive geological interpretation of the factors controlling the coal quality of Seam C. Therefore, this approach has the potential to be applied to exploration, resource evaluation, and mining planning in the Sinamar

Formation as well as other Tertiary coal basins with similar geological characteristics (Dai et al., 2020; Hibatullah et al., 2026; Tang et al., 2020).

5. Conclusion

This study demonstrates that variations in the quality of Seam C coal in the Sinamar Formation are primarily controlled by changes in the depositional environment, while the influence of the degree of coalification is relatively minor. This is indicated by the relatively uniform vitrinite reflectance values (0.44–0.46 %) across all study sites, while petrographic characteristics, coal facies, and coal quality parameters show significant variation. The integration of petrographic analysis with coal facies interpretation using the Tissue Preservation Index (TPI), Gelification Index (GI), Vegetation Index (VI), and Groundwater Index (GWI) indicates that the WBS, LMH, and AKA sites developed in an Upper Delta Plain environment with Telmatic Swamp to Wet Forest Swamp facies under bog-ombrotrophic conditions, whereas the BA1 site underwent a local transition to a Lower Delta Plain environment with a Marsh facies. These changes in the depositional environment led to an increase in the supply of clastic sediments and more dynamic hydrological conditions, as reflected in higher levels of mineral matter, ash, and sulfur, as well as a decrease in the coal's calorific value. Thus, changes in depositional facies are the primary geological factors controlling variations in the quality of Seam C coal.

The integration of descriptive statistical analysis and spatial modeling using Ordinary Kriging shows that the distribution of coal quality exhibits a spatial pattern consistent with interpretations of the depositional environment. Ash and sulfur contents tend to increase in the northern part of the study area, while calorific values are relatively higher in the southwestern part, reflecting differences in sediment supply and environmental conditions during the peat formation process. The results of this study indicate that an integrated approach combining petrographic analysis, coal facies, coal quality, and geostatistics can provide a more comprehensive interpretation of the geological factors controlling the distribution of coal quality than the use of any single method alone. This approach makes a scientific contribution to understanding the relationship between the depositional environment and variations in coal quality in the Sinamar Formation, and can also serve as a more reliable basis for resource evaluation, exploration planning, and mine development in coal basins with similar geological characteristics. Future research is recommended to incorporate more detailed variogram modeling, quantitative geostatistical validation, organic geochemical and sulfur isotope analyses, and three-dimensional geological modeling to gain a more comprehensive understanding of the evolution of the depositional environment and the spatial control of coal quality.

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