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GEOCHEMICAL ATTRIBUTES OF SELECTED NIGERIAN COALS: IMPLICATIONS FOR GRADE AND UTILIZATION

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ABSTRACT

The geochemical attributes which include the proximate and ultimate characteristics of coals were analyzed on selected Nigerian coals to determine their grade and utilization. The key parameters analyzed included moisture content (MC), ash content (AC), volatile matter (VM), phosphorus (P), organic carbon (OC), fixed carbon (FC), total nitrogen (TN), total sulfur (TS), gross calorific value (GCV), and free swelling index (FSI). The conventional methods of coal analyses under the appropriate American Standard for Testing and Measurement (ASTM) and International Standard Organization (ISO) were employed in the coal analysis. The results of the various analyses revealed that moisture content varied across the coals, ash content indicated a significant range, suggesting varying degrees of mineral impurities, moderate to high volatile matter content, indicating good combustibility, phosphorus and organic carbon content varied widely, impacting the coal's suitability for industrial applications, fixed carbon content reflected a range from lignite to bituminous coal, correlating with the samples' energy potential, as indicated by GCV values. These values of the analyzed parameters classify the coals into lignites, sub-bituminous to bituminous grades with various possible utilizations based on the geochemical attributes of the studied coals.

KEY WORDS: Proximate, Ultimate, Geochemical Attributes, Omewe, Ekulu, Anambra Basin

INTRODUCTION

The geochemical attributes of coals play a critical role in determining their grade, industrial and economic applications. Nigeria has several coal deposits spread across different basins, such as the Anambra Basin, Benue Trough, and the Afikpo Sub-Basin (Onoduku, 2013, Jatau, et al, 2021). The primary geochemical characteristics (attributes) influencing the grade and usability of coals include proximate characteristics which include moisture content, fixed carbon content, volatile matter and ash content and ultimate characteristics including organic carbon, sulphur, phosphorous, free swelling index and calorific values of the coals e.g.; lower moisture content is desirable for higher combustion efficiency.

Nigerian coals, particularly those from the study areas, generally have moderate moisture content, which makes them suitable for thermal applications (Onoduku et al., 2018, Jatau and Zakari, 2021).
The ash content of coal affects its calorific value and influences its usability in industrial processes. Nigerian coals generally have relatively low ash content, making them attractive for combustion in power generation and cement industries. Volatile matter on the other hand refers to the components of coal that vaporize when heated. High volatile matter content, found in Nigerian coals such as those from Lafia-Obi, makes them suitable for coking and metallurgical processes. High fixed carbon content increases the coal's energy potential, making it suitable for energy production.

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Many Nigerian coals, particularly from the southeastern region, possess high fixed carbon levels.

Ultimate characteristics on the other hand which include the carbon content of Nigerian coals is a key determinant of their energy potential. Coals with higher carbon content, such as those from the Onyeama and Okpara mines, are preferable for energy production (Ahiarakwem, 2011, Onoduku et al., 2018). The hydrogen content of coal affects its burning characteristics. Nigerian coals generally have moderate hydrogen content, contributing to stable combustion profiles. The nitrogen and sulfur contents are critical for determining the environmental impact of burning coal, as higher sulfur content can result in the emission of sulfur dioxide, leading to acid rain. Nigerian coals, particularly from the Ogboyaga and Okaba mines, have relatively low sulfur content, making them environmentally preferable. The oxygen content, on the other hand, influences the coal's reactivity.

The calorific value of coals is a direct indicator of the energy content of coal. Nigerian coals, especially those from the Anambra Basin, have moderate to high calorific values, making them suitable for power generation and other energy-intensive applications (Onoduku et al, 2024). The Enugu and Okaba coals have been identified as having the highest calorific values in the country (Onyemali, et al, 2017, Onoduku et al., 2018).

Applications of coals based on geochemical attributes include energy generation due to their moderate to high calorific values and relatively low sulfur and ash content, Nigerian coals are well-suited for power generation. Nigerian coals are used in cement production due to their low sulfur content and appropriate ash composition, which helps in reducing clinker formation. Coals with good coking properties, such as those from Lafia-Obi, are suitable for use in the steel industry as metallurgical coke. The relatively low sulfur and high volatile matter of Nigerian coals also make them suitable for domestic heating and cooking purposes. In summary, the geochemical attributes of Nigerian coals, such as their proximate and ultimate characteristics significantly influence their industrial applications. Their low sulfur content and moderate calorific values position them as important resources for energy production, cement manufacturing, and potential use in metallurgical processes.

REGIONAL AND LOCAL GEOLOGICAL SETTINGS OF NIGERIAN COALS

Both the Anambra Basin and Southern Benue Trough coal deposits formed during the Late Cretaceous in a tectonically active region associated with the breakup of Gondwana and the opening of the South Atlantic Ocean.

These basins were characterized by subsidence, which created accommodation space for thick sedimentary sequences, including coal-bearing formations. The coal deposits in both regions vary in thickness and quality. The Anambra Basin, especially the Enugu Coalfield, has thicker and more extensive coal seams compared to the generally thinner seams in the Southern Benue Trough. This combination of tectonic activity, sedimentation, and organic material accumulation led to the formation of significant coal deposits in both regions, making them important coal-bearing areas in Nigeria.

The geological settings of coal deposits in the Anambra Basin and Southern Benue Trough of Nigeria are critical to understanding the formation and characteristics of these coal resources. The Anambra Basin is one of the most significant coal-bearing basins in Nigeria. It is located in the southeastern part of the country and extends across Anambra, Enugu, Delta, and Kogi States. The basin formed during the Late Cretaceous period and is characterized by extensive sedimentary deposits. The coal deposits in the Anambra Basin are primarily from the Maastrichtian age (Late Cretaceous). This period marks the formation of thick sequences of clastic sediments within the Basin (Ahiarakwem, 2011, Onoduku et al., 2018). The coal-bearing strata belong to two primary formations; Mamu Formation (Maastrichtian) which is the primary coal-bearing formation in the Anambra Basin. It consists of alternating sequences of shales, siltstones, fine-grained sandstones, and coal seams. The Ajali Sandstone overlies the Mamu Formation, it is composed of thick layers of cross-bedded sandstones, with intercalations of coal seams and carbonaceous shales. The Anambra Basin developed as a result of the Santonian tectonic movements that created subsidence, leading to the accumulation of thick sediments. The basin is bounded by the Abakaliki Anticlinorium to the east and the Niger Delta to the south. The coal seams in the Mamu Formation are often well-developed, with economically viable deposits. The Enugu Coalfield is one of the most notable coal deposits within the Anambra Basin. Fig. 1(a-b) is the geologic map of Nigeria and the Anambra Basin extending into the Southern Benue Trough.

The Southern Benue Trough is part of the larger Benue Trough, an elongated rift structure that runs in a northeast-southwest direction across Nigeria. The Southern portion is coal-bearing and extends through areas such as Afikpo and Owukpa. The coal deposits in the Southern Benue Trough also formed during the Late Cretaceous, particularly in the Maastrichtian stage. The Southern Benue Trough has coal-bearing formations similar to those in the Anambra Basin.

The key formations are that constitute the sub-basin are Nkporo Formation which is the main coal-bearing unit in the Southern Benue Trough. It is composed of dark shales, siltstones, and coal seams, along with occasional sandstones. The Owelli Sandstone is the unit that contains alternating beds of sandstone and coal seams. The Benue Trough, including its southern section, formed due to the separation of the African and South American plates during the Early Cretaceous. The trough represents a complex rift system that accumulated thick sediments during the rifting process. Coal in this region is typically found in thin seams but is sometimes of high quality, suitable for both power generation and metallurgical use (Onoduku, 2013, Jatau, et al, 2021). The Owukpa Coalfield is one of the notable deposits in the Southern Benue Trough. Figs. 2 and 3 indicate location map and coordinates representation of the sampled and analyzed coal deposits respectively.

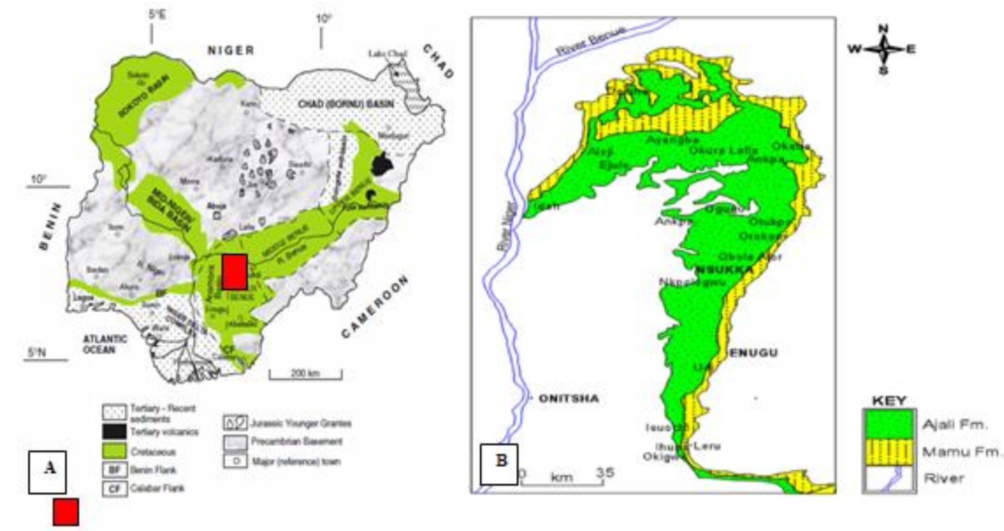

FIG. 1: Geologic Map of Nigeria (A) and Anambra Basin (B) where the study Area is located (After Onoduku et al; 2018).

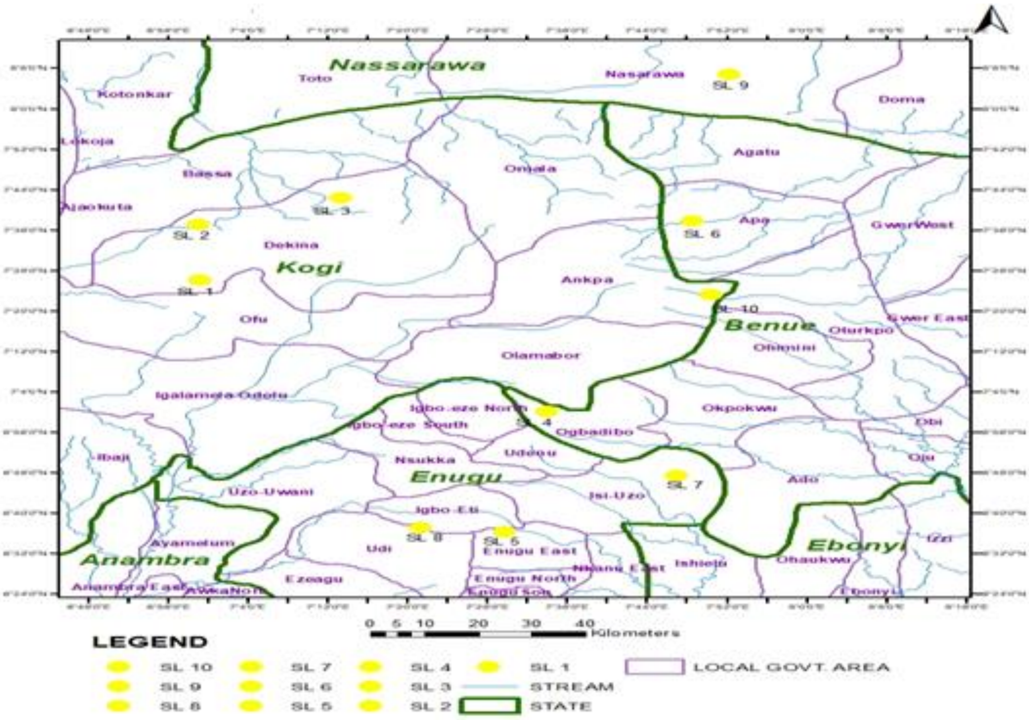

FIG. 2: Location map of the sampled and studied coal deposits

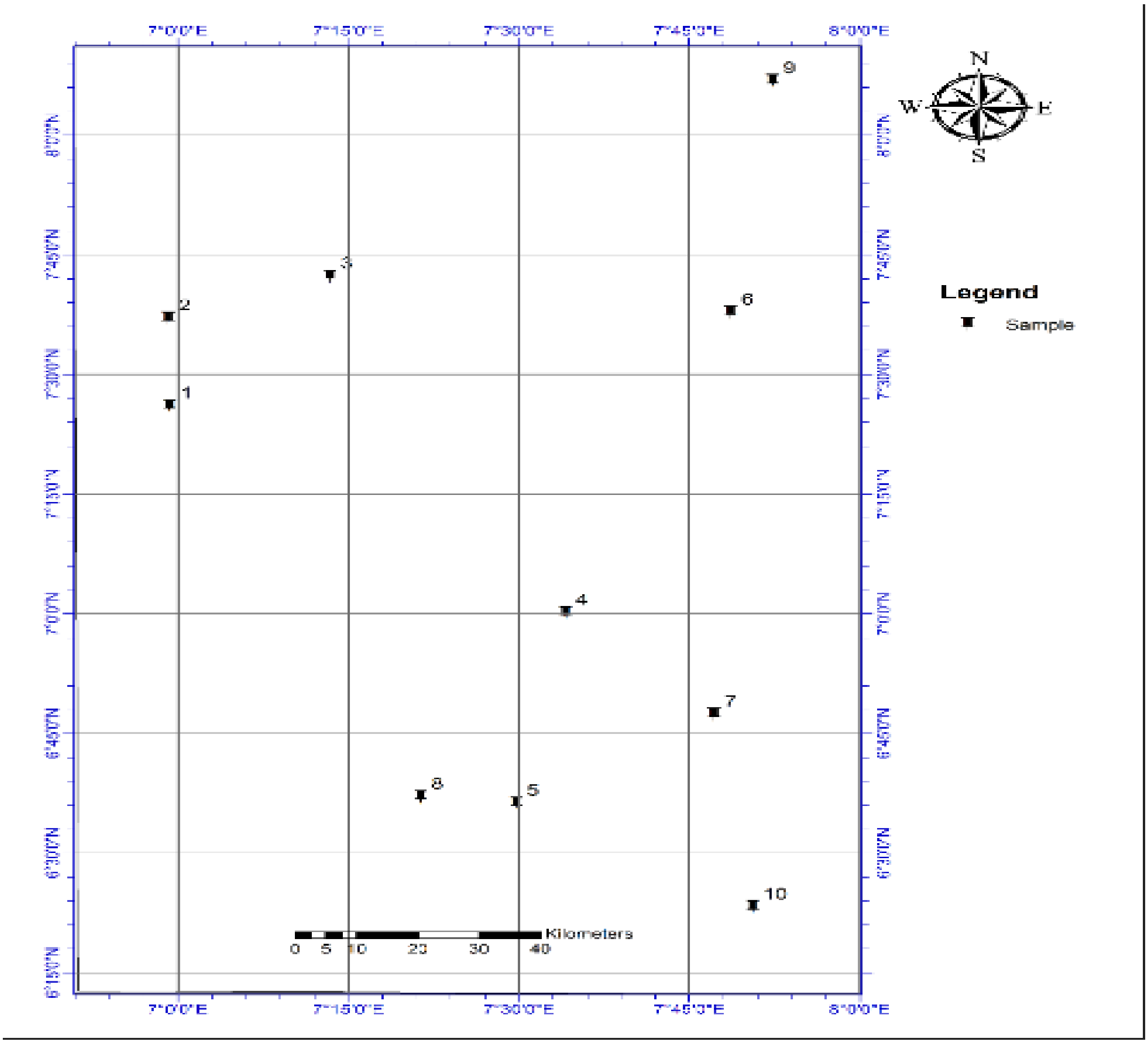

FIG. 3: Sketch map of the areal distributions of the studied coal deposits

METHODS OF ANALYSIS

The coal samples used for the studies were obtained from ten (10) coal deposits within the Anambra basin and southern Benue Trough of Nigeria. Six (6) composite coal samples were obtained from each of the ten coal deposits, totaling sixty (60) coal samples used for the analyses. The coal samples were taken from coal in situ outcrops, coal mines, coal run-off-mines and some core samples. All the coal samples used were grab samples which means the samples were randomly taken during the fieldwork for coal samplings. The proximate and ultimate analyses were performed on fifty coal samples at the Departments of Geology and Soil Science of Kogi State University, Anyagba and ten at Activation Laboratory, Ontario, Canada. All the analyses were carried out on Air Dried (AD) bases. Table 1 summarizes the codes of the specific methods used for the coal analyses

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Table 1: Codes of the methods used for the coal analyses

Analysis/Analyte	Method Code	Reference(s)
Moisture Content	ASTM- D3173	Speight, 2005
Volatile Matter	ASTM- D3175	Speight, 2005
Ash Content	ASTM- D3174	Speight, 2005
Fixed Carbon	ASTM D3172-07a and ISO 17246: 2005	Speight, 2005
Organic Carbon	ASTM- D3178	Speight, 2005
Hydrogen	ASTM- D3178	Speight, 2005
Nitrogen	ASTM- D3179	Speight, 2005
Phosphorous	ASTM-D 3177	Speight, 2005
Sulphur	ASTM-D 3177	Speight, 2005
Free Swelling Index	ASTM-D720	Speight, 2005
Calorific Value	ASTM D5865	Speight, 2005

RESULT AND DISCUSSION

The results of proximate and ultimate analysis for moisture content (MC), ash content (AC), volatile matter (VM), phosphorus (P), organic carbon (OC), total nitrogen (TN), total sulfur (TS), gross calorific value (GCV), free swelling index (FSI), and fixed carbon (FC) are given in Table 2. These results are independently presented, discussed and inferences on their implications for the studied coals grade and utilization drawn and this agrees with some previous works on coals all over the world and Nigeria inclusive e.g.; Sahu et al., 2014, Madanayake et al., 2017, Ullah et al., 2018, Onoduku, 2014a&b, Onoduku et al, 2018, Ahamed et al, 2019 and Onoduku et al, 2024. Coal as a heterogenous geologic material unlike other conventional rocks is a composite earth material whose geochemical attributes viz-a-viz its grade and utilization can be assessed based on individual parameter.

MOISTURE CONTENT (MC)

L1 coal has a moisture content range from 3.55% to 7.12% (average 4.73%), which places it in the anthracite category, reflecting relatively low moisture content. L2 coal shows a moisture range of 2.11% to 3.80% (average 2.77%), indicating it fits within anthracite coal with lower moisture content. L3 coal presents a moisture range from 4.55% to 6.80% (average 5.56%), placing it in the bituminous category with moderate moisture content. L4 coal has a moisture range of 5.88% to 7.56% (average 6.79%), consistent with bituminous coal, reflecting higher moisture levels. L5 ranges from 4.23% to 5.80% (average 4.86%), indicative of anthracite coal. L6 shows a range of 2.45% to 4.90% (average 3.05%), fitting within anthracite coal with lower moisture levels. L7 has a range from 2.80% to 7.30% (average 4.14%), suggesting anthracite coal. L8 ranges from 2.50% to 4.23% (average 3.55%), indicating anthracite coal with relatively low moisture content. L9 presents a moisture range of 0.20% to 4.22% (average 3.64%), suggesting anthracite coal. L10 shows a moisture range from 0.20% to 3.87% (average 2.25%), indicating anthracite coal with low to moderate moisture content (Figure 1).

Moisture content is an essential attributable factor of coal as most coals exploited have some amount of moisture associated with them (Jatau and Zakari, 2021). MC is the loss of weight of coal due to the removal of moisture when heated at about 105°C in a crucible (Kobayashi, 1976; McLaughlin, 1990). The moisture content of coals generally ranges from 5% to nearly 70% which is an undesirable constituent as it reduces the heating value and adds weight to the transportation cost (Sahu et al., 2014; Madanayake et al., 2017). Increased values of this parameter are characteristics of lower-rank coals, while decreased values are typical of higher-rank coals (Ullah et al., 2018). Generally, the moisture content ranges for coal types include; lignite (30% to 65%), sub-bituminous (20% to 30%), bituminous (5% to 20%), and <5% for anthracite (Ahamed et al., 2019)

Table 2: Descriptive statistics of proximate analysis of coal samples

Sample ID	Parameters	MC	AC	VM	P	OC	TN	TS	GCV	FSI	FC
	Minimum	3.55	12.33	16.22	0.11	2.11	0.11	0.12	4100.00	1.50	45.21
L1(Omewe)	Maximum	7.12	18.12	62.20	1.02	3.12	1.01	1.03	4500.00	1.50	71.23
	Average	4.73	15.07	25.42	0.39	2.61	0.32	0.39	4320.00	1.50	59.72
	Minimum	2.11	16.30	28.22	0.23	2.14	0.12	0.12	2290.00	1.00	25.56
L2(Elopa)	Maximum	3.80	33.21	55.20	0.88	3.21	1.12	1.01	2600.00	1.00	40.20
	Average	2.77	25.33	35.53	0.47	2.73	0.56	0.30	2410.00	1.00	30.89
	Minimum	4.55	9.11	27.11	0.32	1.34	0.21	0.11	3219.00	1.00	23.34
L3(Abocho)	Maximum	6.80	15.12	44.30	1.04	3.44	1.01	0.33	3650.00	1.00	44.10
	Average	5.56	11.30	32.99	0.62	2.15	0.39	0.21	3471.50	1.00	31.90
	Minimum	5.88	11.99	12.40	0.33	1.34	0.11	0.11	4238.00	1.00	34.20
L4(Okobo)	Maximum	7.56	23.60	33.21	1.01	2.56	0.76	0.34	4820.00	1.50	65.11
	Average	6.79	17.10	26.75	0.59	1.86	0.31	0.21	4449.00	1.42	54.35
	Minimum	4.23	9.23	11.80	0.43	1.56	0.12	0.22	4170.00	1.50	23.20
L5(Obi-Lafia)	Maximum	5.80	34.20	28.22	0.77	5.21	0.33	0.34	4340.00	1.50	77.11
	Average	4.86	15.67	21.95	0.62	3.08	0.22	0.28	4238.33	1.50	64.68
	Minimum	2.45	12.99	16.80	0.11	2.11	0.12	0.11	6120.00	2.00	18.30
L6(Chikila)	Maximum	4.90	30.30	25.11	1.44	4.23	0.77	0.55	6480.00	2.00	76.23
	Average	3.05	18.76	21.13	0.53	2.60	0.37	0.26	6243.33	2.00	61.75
	Minimum	2.55	16.66	10.30	0.21	1.66	0.14	0.11	5100.00	2.00	42.30
L7(Okpara)	Maximum	7.30	40.20	31.47	1.33	4.11	1.01	0.43	5320.00	2.00	55.99
	Average	4.14	22.83	26.01	0.73	2.36	0.43	0.22	5188.33	2.00	51.70
	Minimum	2.80	18.88	12.10	0.22	1.23	0.12	0.12	3200.00	1.00	44.34
L8(Onyeama)	Maximum	4.23	40.10	45.23	0.54	2.86	0.45	0.33	3880.00	1.00	76.33
	Average	3.55	24.17	31.09	0.39	2.02	0.23	0.24	3441.67	1.00	57.92
	Minimum	2.50	10.23	21.89	0.20	1.23	0.21	0.12	3120.00	1.00	33.50
L9(Ekulu)	Maximum	4.22	33.50	28.11	0.56	2.32	0.64	0.56	3440.00	1.00	77.34
	Average	3.64	15.66	24.28	0.33	1.81	0.37	0.27	3248.33	1.00	62.31
	Minimum	0.20	11.89	1.40	0.10	0.11	0.01	0.10	98.00	0.00	3.20
L10(Odu-Okpakili)	Maximum	3.87	74.20	23.56	0.71	2.11	0.51	0.23	4210.00	1.50	72.11
	Average	2.25	30.11	15.45	0.36	1.35	0.24	0.15	2792.83	1.00	47.04

Ash Content (AC)

L1 coal has an ash content range from 12.33% to 18.12% (average 15.07%), indicating lignite to sub-bituminous coal with moderate to high ash levels. L2 coal shows a range of 16.30% to 33.21% (average 25.33%), suggesting lignite coal with high ash content. L3 presents an ash content range of 9.11% to 15.12% (average 11.30%), placing it in the sub-bituminous category with moderate ash content.

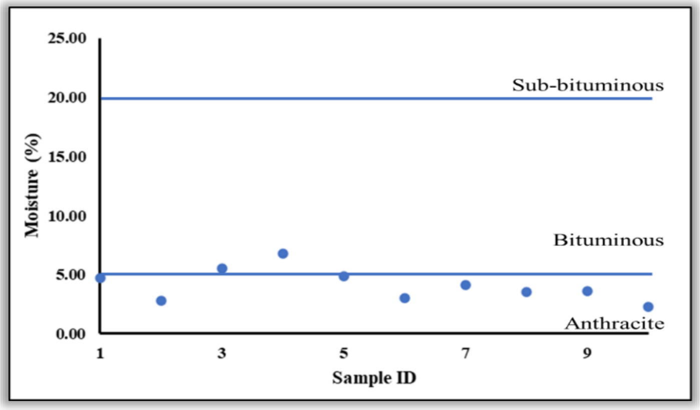

FIG.4: Plot of moisture content against samples indicates that the coal is predominantly anthracitic in rank.

L4 has a range from 11.99% to 23.60% (average 17.10%), consistent with sub-bituminous to lignite coal, reflecting moderate to high ash content. L5 ranges from 9.23% to 34.20% (average 15.67%), indicating a broad range from sub-bituminous to lignite coal with variable ash content. L6 shows a range of 11.99% to 30.30% (average 18.76%), suggesting sub-bituminous to lignite coal with relatively high ash content. L7 has an ash content range of 18.88% to 40.20% (average 22.83%), consistent with lignite coal with high ash content. L8 ranges from 10.23% to 40.10% (average 24.17%), reflecting lignite to sub-bituminous coal with high ash content. L9 presents an ash content ranges from 11.89% to 33.50% (average 15.66%), suggesting sub-bituminous to lignite coal with moderate to high ash levels. L10 shows an ash content range of 11.89% to 74.20% (average 30.11%), indicative of lignite coal with very high ash content, reducing its efficiency.

Ash content determines how much incombustible material remains after coal is burned, affecting its quality and usability (Rasheed et al., 2015). A high ash yield typically indicates a significant presence of detrital materials in swamp environments (Wardle, 2011). In coals with low ash content (8-10%), authigenic minerals are predominant. As the ash yield increases, the proportion of detrital minerals rises and the concentration of organically bound elements decreases (Sahoo and Dey, 2021). The typical ranges include; Lignite (10% to 30%), sub-bituminous (5% to 15%), bituminous (5% to 10%), and anthracite (<10%) (Ikwuagwu and Uzoegbu, 2017).

Volatile Matter (VM)

In L1, volatile matter ranges from 16.22% to 62.20% (average 25.42%), placing it in the sub-bituminous to bituminous range, with good combustibility. L2 has volatile matter from 28.22% to 55.20% (average 35.53%), which is higher, suggesting better combustibility and fitting within the sub-bituminous to lignite category. L3 shows moderate volatile matter content (27.11% to 44.30%, average 32.99%), consistent with sub-bituminous coal that burns efficiently. L4 has a volatile matter range of 12.40% to 33.21% (average 26.75%), typical of sub-bituminous coal. L5 has a volatile matter range from 11.80% to 28.22% (average 21.95%), consistent with lignite coal, which may ignite more slowly. L6 shows lower volatile matter (16.80% to 25.11%, average 21.13%), indicating it is of bituminous rank, suitable for stable combustion. L7 presents a range from 10.30% to 31.47% (average 26.01%), which indicates sub-bituminous coal. L8 has a broader range (12.10% to 45.23%, average 31.09%), indicating good combustion properties and fitting within the sub-bituminous to bituminous range. L9 has a narrower range (21.89% to 28.11%, average 24.28%), suggesting sub-bituminous coal. L10 has the lowest volatile matter (1.40% to 23.56%, average 15.45%), indicating poor ignition properties and suggesting lignite coal.

Volatile matter influences how easily coal ignites and burns, with higher values indicating more efficient combustion (Winarno et al., 2018). The increased VM content is more characteristic of low-rank coals, while the decreased value is more typical of higher-rank coals (Rybak et al., 2019). Typical ranges include; lignite (40% to 60%), sub-bituminous (25% to 40%), bituminous (20% to 30%), and anthracite (<15%) (Kendall et al., 2010).

Phosphorus (P)

L1 has a phosphorus content range from 0.11% to 1.02% (average 0.39%), indicating high levels, which can be detrimental for metallurgical use \and typically reflects sub-bituminous to lignite coal with higher phosphorus content. L2 presents a phosphorus range from 0.23% to 0.88% (average 0.47%), suggesting a moderate level, typical of sub-bituminous coal. L3 shows a phosphorus range of 0.32% to 1.04% (average 0.62%), indicating higher phosphorus content, consistent with bituminous coal. L4 has a phosphorus range of 0.33% to 1.01% (average 0.59%), reflecting bituminous coal with moderate to high phosphorus content. L5 ranges from 0.43% to 0.77% (average 0.62%), indicating moderate phosphorus content typical of sub-bituminous coal. L6 has a phosphorus range of 0.21% to 1.44% (average 0.53%), suggesting higher phosphorus levels, typical of bituminous coal. L7 shows a phosphorus range from 0.22% to 1.33% (average 0.73%), indicating high phosphorus content consistent with bituminous coal. L8 presents a phosphorus range of 0.20% to 0.54% (average 0.39%), indicating a lower level, typical of sub-bituminous to bituminous coal. L9 has a phosphorus range from 0.22% to 0.56% (average 0.33%), reflecting a moderate phosphorus level, typical of sub-bituminous coal. L10 shows a phosphorus range of 0.10% to 0.71% (average 0.36%), indicating moderate phosphorus content consistent with sub-bituminous coal.

Phosphorus content impacts coal's suitability for industrial applications, especially in processes where slagging is a concern. Typical ranges include; lignite (0.05% to 0.20%), sub-bituminous (0.02% to 0.10%), bituminous (0.01% to 0.10%), and anthracite (<0.01%) (Kendall et al., 2010).

Organic Carbon (OC)

L1 shows an organic carbon range from 2.11% to 3.12% (average 2.61%), which is relatively low and consistent with lignite coal. L2 has an organic carbon range of 2.14% to 3.21% (average 2.73%), indicating a low level typical of lignite coal. L3 presents a range from 1.34% to 3.44% (average 2.15%), reflecting a low to moderate level, consistent with lignite coal. L4 shows an organic carbon range of 1.34% to 2.56% (average 1.86%), indicating a low level typical of lignite coal. L5 has an organic carbon range from 1.56% to 5.21% (average 3.08%), reflecting a wider range from lignite to sub-bituminous coal with varying carbon content.

L6 presents an organic carbon range of 1.66% to 4.23% (average 2.60%), indicating lignite to sub-bituminous coal with moderate organic carbon content. L7 shows an organic carbon range of 1.23% to 4.11% (average 2.36%), reflecting lignite coal with varying carbon content. L8 has an organic carbon range from 1.23% to 2.86% (average 2.02%), indicating lignite coal with lower organic carbon content. L9 shows an organic carbon range of 1.23% to 2.32% (average 1.81%), reflecting lignite coal with low organic carbon content. L10 presents an organic carbon range from 0.11% to 2.11% (average 1.35%), indicating lignite coal with very low organic carbon content.

Organic carbon reflects the amount of combustible material in the coal. Typical ranges include; lignite (20% to 35%), sub-bituminous (30% to 50%), bituminous (50% to 75%), anthracite (>75%), (Kendall et al., 2010).

Fixed Carbon (FC)

L1 has a fixed carbon range from 45.21% to 71.23% (average 59.72%), indicating bituminous coal. L2 shows a fixed carbon range of 25.56% to 40.20% (average 30.89%), reflecting lignite to sub-bituminous coal. L3 has a fixed carbon range from 23.34% to 44.10% (average 31.90%), indicating lignite to bituminous coal. L4 presents a fixed carbon range from 34.20% to 65.11% (average 54.35%), reflecting sub-bituminous to bituminous coal. L5 shows a fixed carbon range of 23.20% to 77.11% (average 64.68%), indicating sub-bituminous to bituminous coal. L6 has a fixed carbon range from 42.30% to 76.23% (average 61.75%), suggesting bituminous coal. L7 presents a fixed carbon range from 44.34% to 55.99% (average 51.70%), reflecting bituminous coal. L8 shows a fixed carbon range from 33.50% to 76.33% (average 57.92%), indicating sub-bituminous to bituminous coal. L9 has a fixed carbon range of 33.50% to 77.34% (average 62.31%), reflecting bituminous coal. L10 shows a fixed carbon range from 3.20% to 72.11% (average 47.04%), indicating sub-bituminous coal.

Fixed carbon (FC) is the portion of coal that remains after volatile matter is expelled and represents the combustible portion of the coal. Fixed carbon serves as an estimate of the coke yield from a coal sample. It is calculated by subtracting the mass of the volatiles, as determined by the volatility test, from the initial mass of the coal sample. FC content increases with an increase in coal ranks. Typical ranges include; lignite (25% to 35%), sub-bituminous (40% to 60%), bituminous (45% to 85%), and anthracite (>85%), (Kendall et al., 2010).

Gross Calorific Value (GCV)

L1 has a GCV range from 4100.00 to 4500.00 kcal/kg (average 4320.00 kcal/kg), indicating lignite coal. L2 shows a GCV range of 2290.00 to 2600.00 kcal/kg (average 2410.00 kcal/kg), suggesting lignite coal with lower energy content. L3 has a GCV range from 3219.00 to 3650.00 kcal/kg (average 3471.50 kcal/kg), reflecting lignite coal. L4 presents a GCV range of 4170.00 to 4820.00 kcal/kg (average 4449.00 kcal/kg), indicating sub-bituminous to lignite coal. L5 shows a GCV range from 3120.00 to 4340.00 kcal/kg (average 4238.33 kcal/kg), reflecting lignite coal. L6 has a GCV range from 5100.00 to 6480.00 kcal/kg (average 6243.33 kcal/kg), suggesting bituminous coal with higher energy content. L7 presents a GCV range of 3200.00 to 5320.00 kcal/kg (average 5188.33 kcal/kg), indicating sub-bituminous coal. L8 shows a GCV range from 3120.00 to 3880.00 kcal/kg (average 3441.67 kcal/kg), reflecting lignite coal. L9 has a GCV range of 3200.00 to 3440.00 kcal/kg (average 3248.33 kcal/kg), consistent with lignite coal. L10 presents a GCV range from 98.00 to 4210.00 kcal/kg (average 2792.83 kcal/kg), indicating lignite coal with a lower energy content (Figure 2).

Gross calorific value (GCV) measures the energy content of coal (Jatau and Zakari, 2021). Typical ranges include; lignite (2,000 to 4,500 kcal/kg), sub-bituminous (4,500 to 6,000 kcal/kg), bituminous (6,000 to 7000 kcal/kg), and anthracite (7000 to 8000 kcal/kg), (Kendall et al., 2010).

Free Swelling Index (FSI)

L1 has an FSI of 1.50, indicating moderate swelling characteristic typical of bituminous coal. L2 also has an FSI of 1.00, suggesting lower swelling capacity, typical of lignite coal. L3 has an FSI of 1.00, indicating a similar swelling characteristic as lignite coal. L4 shows an FSI of 1.42, suggesting moderate swelling capacity, consistent with bituminous coal. L5 has an FSI of 1.50, indicating moderate swelling capacity, typical of bituminous coal. L6 shows an FSI of 2.00, indicating high swelling capacity, which is often associated with bituminous to semi-anthracite coal. L7 has an FSI of 2.00, reflecting high swelling characteristic consistent with bituminous to semi-anthracite coal. L8 has an FSI of 1.00, indicating lower swelling capacity, consistent with lignite coal. L9 has an FSI of 1.00, similar to lignite coal with lower swelling properties. L10 has an FSI of 1.00, indicating lower swelling capacity, fitting lignite coal.

The Free Swelling Index measures the coal's ability to swell when heated, impacting its coking properties. Typical FSI ranges include; lignite (0 to 2), sub-bituminous (1 to 3), bituminous (3 to 6), and anthracite (>6), (Kendall et al., 2010).

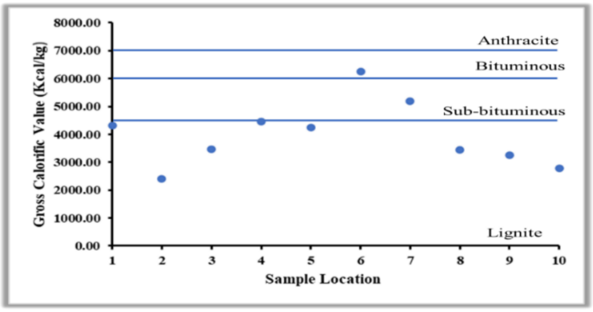

FIG.5: Plot of gross calorific values of coal against samples

Total Nitrogen (TN)

L1 shows a nitrogen range from 0.11% to 1.01% (average 0.32%), indicating a range typical of lignite coal. L2 presents a nitrogen range of 0.12% to 1.12% (average 0.56%), reflecting lignite to sub-bituminous coal with higher nitrogen content. L3 has a nitrogen range from 0.21% to 1.01% (average 0.39%), consistent with lignite coal. L4 shows a nitrogen range of 0.12% to 0.76% (average 0.31%), indicative of lignite coal. L5 has a nitrogen range from 0.12% to 0.33% (average 0.22%), reflecting lower nitrogen content typical of lignite coal. L6 shows a nitrogen range from 0.14% to 0.77% (average 0.37%), indicating lignite to sub-bituminous coal. L7 has a nitrogen range of 0.12% to 1.01% (average 0.43%), reflecting lignite to sub-bituminous coal. L8 shows a nitrogen range from 0.21% to 0.45% (average 0.23%), indicative of lignite coal with lower nitrogen content. L9 has a nitrogen range from 0.12% to 0.64% (average 0.37%), suggesting lignite to sub-bituminous coal. L10 shows a nitrogen range of 0.01% to 0.51% (average 0.24%), indicating lignite coal with low nitrogen content.

Total nitrogen content affects the coal's combustibility and pollution potential. Typical ranges include; lignite (0.5% to 1.0%), sub-bituminous (0.5% to 1.0%), bituminous (0.5% to 1.0%), and anthracite (<0.5%), (Kendall et al., 2010).

Total Sulfur (TS)

L1 shows a sulfur range from 0.12% to 1.03% (average 0.39%), indicating lignite to sub-bituminous coal with moderate sulfur content. L2 has a sulfur range of 0.12% to 1.01% (average 0.30%), suggesting lignite coal with lower sulfur content. L3 shows a sulfur range from 0.11% to 0.33% (average 0.21%), indicative of lignite coal with low sulfur content. L4 presents a sulfur range of 0.11% to 0.34% (average 0.21%), consistent with lignite coal. L5 ranges from 0.22% to 0.34% (average 0.28%), indicating lignite coal with lower sulfur content. L6 shows a sulfur range from 0.11% to 0.55% (average 0.26%), reflecting lignite to sub-bituminous coal with moderate sulfur content. L7 has a sulfur range of 0.12% to 0.43% (average 0.22%), indicating lignite coal with lower sulfur content. L8 shows a sulfur range from 0.12% to 0.33% (average 0.24%), reflecting lignite coal with low sulfur content. L9 presents a sulfur range from 0.11% to 0.56% (average 0.27%), indicating lignite coal with low sulfur content. L10 has a sulfur range from 0.10% to 0.51% (average 0.15%), reflecting lignite coal with very low sulfur content. The summary of the Coals classification by location is given in Table 3.

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Total sulfur content affects the coal's environmental impact and combustibility. Typical ranges include; lignite (0.5% to 2.5%), sub-bituminous (0.1% to 1.0%), bituminous (0.5% to 3.0%), and anthracite (<1.0%), (Kendall et al., 2010).

APPLICATIONS OF THE ANALYSED COALS

Based on the analysed proximate and ultimate characteristics of the studied coal deposits versus their potential uses, it is obvious that there exists a nexus between the characteristics of the coals and their physicochemical characteristics. Also, these studied coal deposits are classified into one of five inferred coal ranks; namely, lignite, lignite-sub-bituminous, sub-bituminous-bituminous, sub-bituminous and bituminous ranks based on their characteristics. Thus, the lignitous coals include the Elopa and Odu-Okpakili coal deposits, the lignite-sub-bituminous coal is the Onyeama coal deposit, the sub-bituminous-bituminous coals are Okobo and Obi-Lafia coal deposits, the sub-bituminous coals are the Omewe and Abocho coal deposits while the bituminous coals include the Chikali,Okpara and Ekulu coal deposits (Table 3). From Table 3, the various uses of the analysed coal deposits based on their physicochemical characteristics are summarized in Table 4.

CONCLUSION

The studied coals from the ten coal deposits spread across the Anambra basin and Southern Benue Trough of Nigeria exhibit varied levels of concentration in terms of their proximate and ultimate characteristics. These varied physicochemical characteristics on which the coals' uses are based are as shown in Table 2 and 3. Nigeria

The geochemistry of the studied coals reveals that they are primarily lignitous to bituminous, with varying degrees of rank and quality. These coals contain varying amounts of fixed carbon, moisture contents, volatile matters and ash contents coupled with various amounts of N, C, H, P and S, influencing their combustion properties and environmental impacts

Table 3: Summary of the coal's classification from L1 to L10

The studied coals have several potential uses based on their ranks including energy production, coke production, coal chemicals, domestic uses, industrial uses, CTL productions.

In overall, while Nigerian coal have significant economic potential, their development requires improved processing technologies and environmental management strategies to optimize their benefits and minimize negative impacts. **Sample ID**	**Characteristics**	**Rank of Coal**
L1(Omewe)	moderate to high energy content, fixed carbon, and variable phosphorus levels.	sub-bituminous
L2(Elopa)	lower energy content, fixed carbon, and organic carbon, with moderate to low phosphorus levels.	lignite coal
L3(Abocho)	a range of fixed carbon and phosphorus levels, moderate energy content, and lower nitrogen content.	sub-bituminous
L4(Okobo)	high fixed carbon and energy content, and moderate phosphorus levels.	sub-bituminous to bituminous
L5(Obi-Lafia)	high fixed carbon and variable phosphorus levels.	sub-bituminous to bituminous
L6(Chikali)	high energy content, fixed carbon, and sulfur levels.	Bituminous
L7(Okpara)	high energy content, moderate to high sulfur, and phosphorus levels.	Bituminous
L8(Onyeama)	lower fixed carbon and sulfur content, and moderate energy content.	lignite to sub-bituminous
L9(Ekulu)	higher fixed carbon, sulfur, and phosphorus content.	Bituminous
L10(Odu-Okpakili)	very low energy content, lower fixed carbon, and phosphorus levels.	Lignite

Table 4: Inferred Uses of the Analysed Coal Deposits Based on Their Ranks

S/No	Coal Deposits	Coal Rank	Inferred Uses	Remarks
1.	Elopa and Odu-Okpakili	Lignite	Electric generations in power plants, Cement production, Gasification, Briquetting, Fertilizer production, Carbon sequestration, Activated carbon production and Coal-To-Liquid (CTL) Technology,	Appropriate beneficiation method is highly recommended
2.	Onyeama	Lignite-Sub-Bituminous	Electricity generation in Thermal Power Plants and coal gasification, Cement and Lime Production in the form of cement kilns and lime respectively, Chemical Feedstock for CTL and Coal-to-Olefin, Metallurgical Use in coke production, Agriculture in the form of soil conditioner and biochar production, Brick production from the coal fly ash, Carbon sequestration, Gasification, Coal briquettes, Activated carbon production.	Appropriate beneficiation and blending are recommended
3.	Okobo and Obi-Lafia	Sub-Bituminous-Bituminous	Electricity generation in Coal-fired power plants and Co-generation plants, Cement manufacturing via fuel for kilns and fly ash production, coking for metallurgical applications in steel production, Domestic and industrial heating as boiler fuels and house hold uses, CTL applications, Chemical feedstock for water and air filtration, Coal briquetting, Carbon Black Production for rubber and plastic industries, Agricultural uses,	Appropriate beneficiation and coal blending in recommended ratios are recommended.
4.	Omewe and Abocho	Sub-Bituminous	Electricity generation, Cement manufacturing, Industrial boilers, CTL. Spce heating, Gasification, Metallugical processes, Environmental control Technologies, and Coal blending	Appropriate beneficiation and coal blending in recommended ratios are recommended.
5.	Chikali, Okpara and Ekulu	Bituminous	Electricity generation, Cement manufacturing, Steel and metallurgical industries, CTL, Industrial heating, Gasification for chemicals and fertilizers, Residential and commercial heating, Coal blending, Coal briquettes, Carbon products, Export marketing.	Appropriate blending is recommended.

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