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Evaluating the Geochemical Properties of Awhum Coal and its Potential for Sustainable Energy Generation and Optimization in Nigeria

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Abstract

Nigeria is today faced with numerous challenges in its attempt to fulfil its increasing energy demands. This paper seeks to examine the opportunities that coal as an energy resource presents, particularly for a developing country like Nigeria. The purpose of this study is to carry out an exhaustive geochemical analysis of selected Awhum coals from the African Pit and Quarry (APQ) site with particular emphasis on their suitability for energy production and their attendant economic and social impact on the environment. To accomplish this, both ultimate and proximate analyses were conducted on the coal samples which were sourced from Awhum site. The accumulation of coal with a high level of carbon and hydrogen was estimated; nitrogen, sulfur and oxygen were estimated to be low. In particular, nitrogen and sulfur amount were defined as 1.07 and 0.39% wt, respectively. The proximate analysis results gave moisture content of 4.40 wt.%, volatile matter of 51.16 wt.%, fixed carbon of 40.63 wt.% while the ash content was 3.81 wt.% which all reflect the potential of the produced energy**.** APQ coal has ahigher heating value (HHV) of 23.74 MJ/kg, this is due to the low carbon (C), hydrogen (H) and high oxygen (O) content in APQ. Based on theAmerican Society for Testing and Materials (ASTM)D388 standard, the coals were classified as Sub-bituminous (Black) low-rank coals (LRCs) with an impressive potential for energy recovery. The properties of this coal make it suitable for industrial and domestic heating, and electric power generation, coke blending or co-firing with biomass for energy recovery through pyrolysis, gasification or combustion.

Keywords: Awhum coal, proximate analysis, ultimate analysis, value index and volatile matter

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Introduction

Coal in Nigeria has long been underutilized despite the country's abundant coal reserves. The once vibrant coal industry in Nigeria has dwindled over the years due to various factors such as the discovery of oil, environmental concerns, and the shift towards cleaner energy sources [1]. However, there is a growing realization of the importance of diversifying energy sources and the need for sustainable energy solutions [2]. Nigeria is showing renewed enthusiasm for a coal energy economy. Yet, the absence of detailed information on the physical, chemical, thermal kinetics, thermodynamic properties, and environmental sustainability are factors impeding the shift to coal energy.

Coal should be reconsidered in Nigeria for several reasons. Firstly, utilizing coal can help reduce the country's heavy reliance on oil and gas, providing a more balanced energy portfolio. Additionally, with modern technologies, coal can be used more efficiently and cleanly, minimizing its environmental impact. Reviving the coal industry can also create job opportunities, stimulate economic growth, and enhance energy security in Nigeria. By harnessing its coal resources responsibly, Nigeria can achieve energy independence and contribute to a more sustainable future [3].

As a result, this study intends to identify the fuel characteristics, rank classification, and possible applications of Awhum coal in Enugu State, Nigeria. The elemental and calorific fuel properties of the coals will be assessed using ultimate, proximate, and bomb calorific analyses. It is expected that the results will provide necessary design and optimization data for future thermochemical coal conversion.

The accessibility and geology of Awhum

The study area and environs lie within the Mamu Formation, Ajali Formation, and Nsukka Formation, which is the lithostratigraphic unit of the Lower Maastrichtian to the Upper Maastrichtian succession of the Anambra Basin. The study area lies within latitude 060 291’ 011”N and 060 341’ 011”N, and longitude 0070 231’ 011”E and 0070 271’ 011”E with an area extent of 69.192 km²on a scale of 1:30000. The area extends from Ukana to Okpatu; other areas covered include Amani, Ibite, ESBS mast station, old Nsukka road, Awhum-Egede road, Okofia, and Awhum monastery road. It is mostly accessible through the old 9th mile – Nsukka road, which forms the major road, and through the 9th mile – Makurdi expressway via the Egede-Awhum road path. Awhum is a popular tourist and pilgrimage destination, attracting visitors with its waterfalls, caves, beautiful streams, and active monastery, the first in Nigeria.

The study area is purely a sedimentary terrain without any evidence of intrusion of igneous rocks, and it has not been subjected to high temperature and pressure that can lead to metamorphism. It consists of lithological units correlatable to three major geologic formations: Mamu, Ajali, and Nsukka Formations. The Mamu Formation (Lower Maastrichitian) is the oldest formation in the study area and is composed of sandstone, mudstone, sandy shale, and coal seams. It has a thickness of about 400m. Plant remains are abundant in coals. The Ajali Formation, which is overlying the Mamu Formation, consists of white, purple, yellow, and red-colored sandstone; it is loose, friable, and non-fossiliferous. The Nsukka Formation, which is the youngest formation and also known as the upper coal measure, consists of reddish-brown ironstone that is pebbly to boulder-sized; it is highly ferrogenized. The geologic map and the cross-section of the study area are given in Fig. 1.

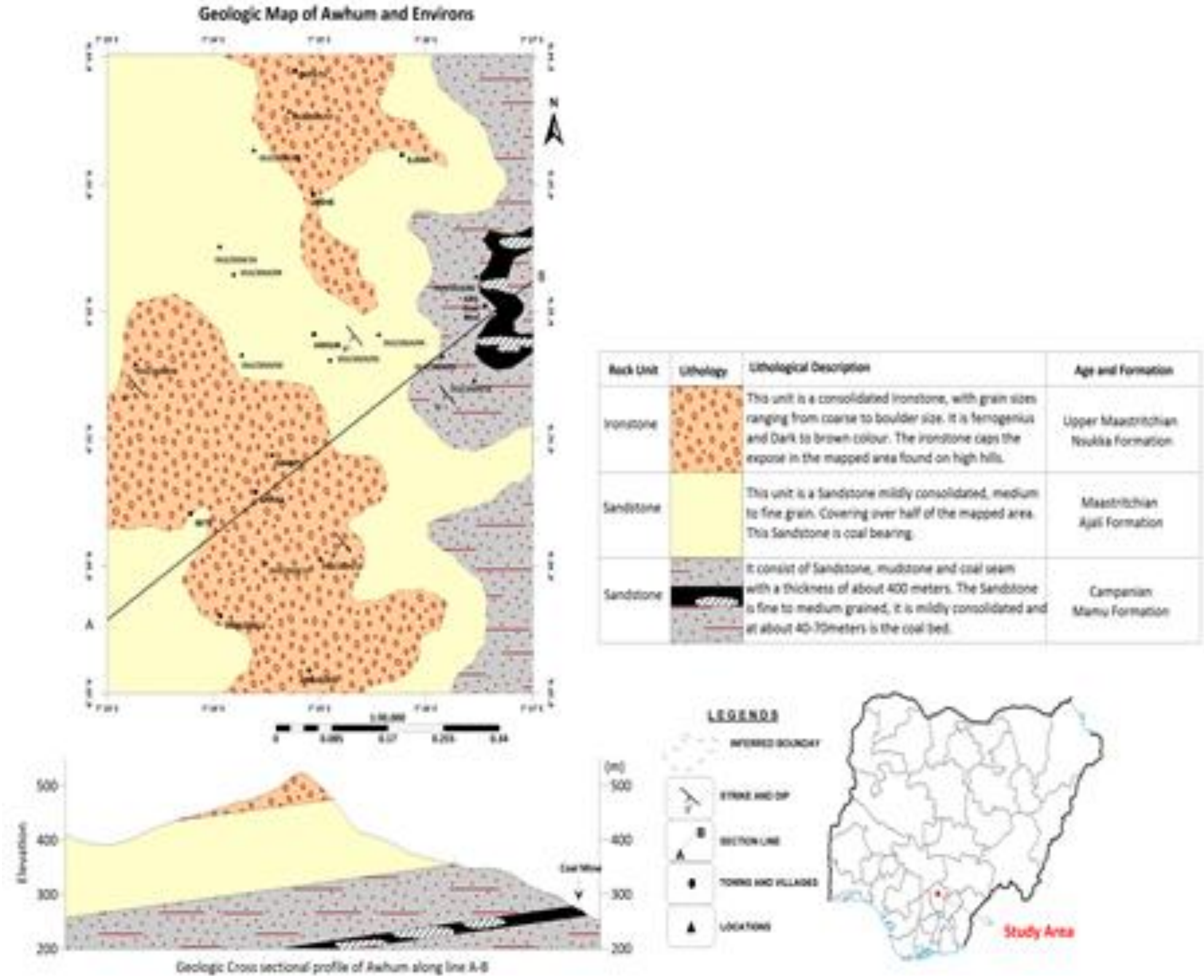

Figure 1: Location and geological map of the study area

Materials and Methods

A coal sample from the mine site at African pits and quarry, Awhum (Fig. 2), was obtained manually, kept in an airtight polyethylene bag, and labeled as APQ prior to analysis. The sample was taken to the laboratory for the analysis. The air-dried sample obtained was reduced both in particle size and quantity to yield a laboratory sample by crushing to a fine powder with the aid of a hammer and aluminum tab and sifted using the Retsch™ analytic sieve of mesh size 60 to acquire 250 µm sized particles prior to characterization. The pulverized coal sample was subsequently characterized by ultimate and proximate analyses to examine the fuel characteristics required for rank classification. The ultimate analysis was determined using a CHNS elemental analyzer (Model: vario MICRO CubeTM, Germany). The analysis was carried out in duplicate, according to the ASTM D5291 [8] standard and the results were analyzed using the CHNS analysis software (version 3.1.1). The proximate analysis was examined by thermogravimetric (TG) analysis on the sample, and average values obtained were used for further deductions.

Figure 2: Coal exposure at the African pits and quarry mine

The calorific (higher heating) value was determined using a bomb calorimeter (Model: IKA C2000, USA) according to ASTM D2015 [8], whereas the lower heating value (LHV) was calculated as described by Eq. 1 [2]. The mineral matter (Mm) content of the fuel was calculated from the Parr formula [4].

$$LHV = HHV - (22.604 \times H) - (2.581 \times MC) \quad (1)$$
$$Mm = (1.08 \times AC) + (0.55 \times S) \quad (2)$$

The terms in Eqs 1 and 2 represent LHV – Lower Heating Value (MJ/kg); HHV – Higher Heating Value (MJ/kg); H – Hydrogen content; MC – Moisture content; Mm – Mineral Matter; AC – Ash and S – Sulphur content. Lastly, the rank classification of the coals was examined according to the procedures of the ASTM D388 standard.

Based on the ultimate and proximate analyses of the coal, the atomic and fuel property ratios were determined based on relations;

Lower Heating Value $LHV = HHV - (22.604\ x\ H) - (2.581\ x\ MC)$ (3)

Mineral Matter $Mm = (1.08\ x\ AC) + (0.55\ x\ S)$ (4)

Combustible to Pollutant Ratio C+H/(N+S) (5)

Heating Value to Pollutant Ratio HHV/(N+S) (6)

Heating Value to Combustible HHV/(C+H) (7)

Fuel Ratio FC/VM (8)

Fuel Value Index HHV/AC+MC (9)

The atomic and fuel value ratios for the Awhum coal sample is presented in Table 5 as deduced from the ultimate and proximate analyses in Tables 1 and 2.

Results and Discussion

Ultimate/elemental analyses

The results for the elemental composition and the calorific value of the coal are presented in Table 1 below with all values reported as received based on the analysis conducted. As observed in Table 1, the *H, N, and S* values for the coal sample examined in this study are in good agreement. However, the *C* and *O* values are markedly different due to the typical variation in the fuel properties of different ranks of coals.

Table 1: Ultimate analysis of Awhum coal

Property	Symbol	Awhum Coal Sample value (wt. %)	Expected Value range (%)			
			Lignite	Sub-Bituminous	Bituminous	Anthracite
Carbon	C (%)	61.96	60-70	70-76	75-85	85-95
Hydrogen	H	4.42	4.0-5.0	4.0-5.5	4.5-5.5	2.5-3.5
Nitrogen	N	1.07	0.5-1.0	05.-1.0	1.0-2.0	0.5-1.0
Sulphur	S	0.39	0.5-2.0	0.5-2.0	0.5-3.0	0.5-1.0
Oxygen	O	32.16	20-30	15-25	5-15	2-5
Heating value	HHV	23.74	10-20	18-25	25-32	30-35

As can be observed in Table 1, the coal samples possess high C, H, and O content. However, low values were also obtained for N and S during elemental analysis.
The C and H content of coals is significantly related to the maturity (rank), calorific value, and chemical reactivity during thermal conversion [5, 6].
The N and S content is an indication of the environmental friendliness of the fuels relative to potential NO_x and SO_x pollutant emissions. Overall, Awhum coal showed a low N and S content and may be considered the coal with low potential environmental pollutants. According to Ryemshak and Jauro [6], the properties of Awhum coal are suitable for cement and steel manufacture, power generation, and industrial and domestic heating.

The average calorific or heating value of the coal is 23.74 MJ/kg. Furthermore, the calorific values for the coal are consistent with the C and O content of the coals (ASTM D 3176) [8]. Hence, the results indicate that there is an increase in reactivity and maturity of the coal in Awhum.

Proximate analysis

The results of proximate analysis and mineral matter of the coal, reported in as received, are presented in terms of moisture content (MC), volatile matter (VM), fixed carbon (FC), and ash content (AC) along with the calculated values for fuel ratio and mineral matter. As observed, the average moisture content of AFQ is 4.40 wt.%, and the volatile matter, fixed carbon, and ash content of AFQ are 51.16, 40.63, and 3.81 wt.%, respectively.

Determination of percentage moisture content of coal sample

The Moisture Content (MC) is an important parameter for handling, storage, and transport (HST) of coal. In addition, it is an indicator of the heat energy potential or operational costs required to dry, co-fire, or convert coal in power plants [7, 9].

Table 2: Determination of percentage moisture content of coal sample

S/N	Weight of sample Wo (g)	Weight of Empty Crucible W1 (g)	Weight of Crucible + Sample before heating W2 (g)	Weight of Crucible + Sample after heating W3 (g)	Loss in Weight = W2-W3	% Moisture Content = (W2-W3)/Wo*100
1.	2.007	16.238	18.245	18.150	0.095	2.358
2.	2.010	15.099	17.110	17.008	0.102	5.075
3.	2.007	17.027	19.086	18.987	0.049	2.442
4.	2.010	15.538	17.548	17.432	0.116	5.771
5.	2.010	17.260	19.271	19.143	0.128	6.368

Total Average = 4.403

Table 3: Determination of percentage ash content of coal sample

S/N	Weight of Sample Wo (g)	Weight of Empty Crucible W1 (g)	Weight of Crucible + Sample before AshingW2 (g)	Weight of Crucible + Sample after Ashing W3 (g)	% Ash Content = (W3-W1)/Wo*100
1.	2.014	16. 935	18.950	16.970	1.738
2.	2.017	15.265	17.283	15.296	1.570
3.	2.019	15.956	17.976	16.077	5.993
4.	2.003	18.203	20.208	18.322	5.941

Total Average = 3.8105

Determination of percentage ash content of coal sample

The average Ash Content (AC) of APQ coal is about 3.8105 as observed in Table 3. Ash is the non-combustible residual or mineral matter produced from coal combustion. Similarly, another research showed that, ash significantly affects waste handling, processing, and utilization equipment [1]. In addition, the chemical composition of ash is a measure of the fouling, slagging and agglomeration potential of coal in conversion equipment. Consequently, lower ash, as observed in APQ, is preferable from a cost and operational perspective. (ASTM D 3174)[8].

The Volatile Matter (VM) significantly influences the thermochemical reactivity, rank classification, and conversion efficiency of coal. In addition, it is a measure of condensable and non-condensable volatile compounds generated from the thermal decomposition of coal under given reaction conditions. The higher volatile matter of APQ is suitable for syngas production through pyrolysis and gasification technologies.

The Fixed Carbon (FC) is the solid carbonaceous residue from drying and de-volatilization typically used to estimate the coke (coking) potential and rank classification of coals. Based on the findings of this study, APQ has a higher potential for coke formation and fuel ratio, which is an important factor for metallurgical coal applications, energy recovery, and electric power generation.

Based on the proximate analysis, the Fuel Ratio and Fuel Value Index of the APQ coals were deduced as presented in Table 5. The results indicate that the fuel ratio and value index of the APQ coal is due to the amount of moisture, ash content and volatile matter content present in the coal as presented in Table 4.

Table 4: Summary of the proximate analysis and calorific values of APQ coal

Fuel Property	Symbol	Average AFQ (wt. %)
Moisture Content	MC	4.40
Volatile Matter	VM	51.16
Ash Content	AC	3.81
Fixed Carbon	FC	40.63
Mineral Matter	Mm	3.11

Table 5: Fuel ratios for APQ coal sample

Fuel Property	Symbol	AFQ (wt. %)
Fuel Ratio	FC/VM	0.79
Fuel Value Index	HHV/AC+MC	2.89

Coal rank and classification

The rank classification of the coals was examined according to ASTM D388 [8]. According to the standard, the coals are classified as *sub-bituminous* based on HHVs which are less than 24 MJ/kg. The sub-classification analysis indicates that APQ is *sub-bituminous* coal class B. The result aligns with the findings of Uzoegbu and Uhegbu [10].

The properties of the coal samples analyzed in this study demonstrate their potential suitability for energy generation, aligning with global standards. The proximate analysis revealed that the samples possess a relatively high calorific value, low moisture content, and moderate to high fixed carbon content, which are critical indicators of coal quality for efficient combustion and power generation. These findings are consistent with previous studies [11, 12], which have established that coals with higher fixed carbon and calorific values exhibit better thermal efficiency and lower emissions. Furthermore, the ash content recorded in this study falls within acceptable limits outlined by international coal classification standards such as those set by ASTM and ISO (ISO 11760:2018; ASTM D388-19). Comparatively, our sulfur analysis indicates that the coal samples have low to moderate sulfur content, suggesting minimal environmental impact upon combustion, which aligns with findings from similar studies on clean coal technologies [13, 14]. Therefore, the coal samples analyzed in this study meet the fundamental criteria for energy generation, comparable to internationally recognized coal reserves.

In general, the Awhum coal is black or low-rank coals (LRCs) with non-caking properties. This indicates the coal can be potentially utilized for electric power generation, coke blending, or co-firing with biomass for energy recovery through pyrolysis, gasification, or combustion.

Conclusion

This paper investigated the fuel properties, rank and classification of the coal in the Awhum. The characterization was based on ultimate and proximate analysis. The results indicated the coal sample contain sufficient proportions of combustible elements for various energy recovery, power, and metallurgical applications. Furthermore, the fuel characterization indicated that APQ- African Pit & Quarries coal has a great handling, storage, and transport capabilities. APQ has a high fuel ratio and value index due its low moisture content, ash content and volatile matter. The rank classification indicates the coals are Sub-bituminous (Black) Low-Rank Coals (LRCs) with potential for electricity generation or biomass co-firing for enhanced energy recovery and fuels synthesis. More so, the coal characteristics presented in this study can be utilized for the design, optimization, and scale-up of future conversion systems for energy recovery.

Competing of interest: There is no competing interest on this article.

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