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Coal chemistry, utilization potential, and coalbed methane (CBM) assessment of some coal deposits in Central Benue Trough, north-central Nigeria

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Received: 27 March 2024 / Accepted: 21 August 2024
Published online: 03 September 2024
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Abstract
Coalbed methane (CBM), a current global legislative priority for climate change mitigation, is an unconventional and eco-friendly clean source of energy that is considered a veritable alternative to conventional fossil fuels. Despite its overwhelming advantages, CBM evaluation studies of Nigerian coals have received little or no attention. To bridge the gap in knowledge, we have for the first time in Jangwa-Shankodi and Lafia-Obi, described the potential of harnessing CBM for its gainful utilization in Nigeria using some coal deposits in its north-central region as a case study. The gas contents of the coals were determined empirically by taking account of their ultimate and proximate properties. Other coal parameters such as fuel ratio and vitrinite reflectance (R_o (%)) have also been computed and discussed. Proximate analyses of the studied coal samples show moisture contents that vary between 2.28 and 2.56%, whereas, volatile matter yield is placed in the range of 29.98–30.34%. Ash yield ranges from 7.83 to 8.64%. Fixed carbon content varies from 55.97 to 56.30%. Variation in fuel ratio shows a restricted range from 1.72 to 1.87. All the coal samples were found to be low in sulphur (< 1%) with H/C ratios that vary from 0.072 (LAF 2, 3 and 4) to 0.086 (JSK 3). Moreover, the coals were found to be of medium-volatile bituminous rank, with gas contents that range from 12.65 to 13.20 cc/g. In the current study, kerogen lies in the Type IV zone, which suggests the generation of methane gas by the studied coal samples. Also the estimated range of vitrinite reflectance (R_o) which varies between 1.073% and 1.086% indicates thermogenic gas expulsion in the coals. There is a noticeable increase in gas content with coal maturity and depth. These values are indicative of good quality coals that show antecedents for CBM production. However, considering that this work is a pilot study, we recommend that core drilling be employed in obtaining insitu measurements of the coal gas contents and thus, verify these empirical estimates. Also, detailed laboratory study on pore structure (and its distribution) and adsorption isotherm curve are recommended to better understand the coal reservoir properties and hence, consolidate the present study.

Keywords Lafia-Obi · Jangwa-Shankodi · Central Benue trough · Coalbed methane · Ultimate analysis · Proximate analysis

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1 Introduction

Internationally, conventional energy sources such as crude oil and natural gas have the highest share in energy mix [1]. These energy sources have found useful applications in diverse domestic and industrial ventures worldwide, and are currently the main focus of global energy demand. However, their exploitation has been accompanied by the emission of harmful anthropogenic greenhouse gases (GHGs) throughout the climate system [1–3]. The United Nations Intergovernmental Panel on Climate Change (IPCC) reported that the mean global temperature has increased by 0.6 ± 0.2 °C and may increase by 1.4–5.8 by 2100 [1, 4]. As a result, the demand for environmentally friendly resources including shale gas, solar energy, wind energy and hydrogen gas has been on the increase globally. Recently, changes in key market drivers globally have also led to the search for, and development of, unconventional energy resources such as coalbed methane (CBM), as an alternative [1, 3–5]. It is believed that a switch from conventional natural gas sources to CBM will drastically reduce GHGs emissions thereby preventing their build-up in the atmosphere and its associated climatic effect [2, 4–6]. Methane gas entrapped within the matrix of coal seams constitute an important source of clean fossil energy that could be extracted for commercial utilization [3, 5–10]. The variation in the methane gas content is usually dependent on coal rank, which is in turn determined by coal chemistry [4, 5, 9–11].

In Nigeria, economically important coal seams occur in diverse sedimentary formations and cover areas such as Enugu, Eha-Alumona, Ehandiagu, Agbogugu, Inyi, Okaba, Maiganga and Tai Shankodi, Jangwa, Obi and Lafia, all within southeastern, north-central and northeastern parts of the country with an estimated measured reserve of about 2 Gt [12]. Its reserve is equivalent to 1,961.4 times its consumption annually, which gives leverage for methane gas production. Unfortunately, no work has been previously carried out explore the potentiality of these coal deposits for CBM recovery except for the Eha-Alumona and Ehandiagu coal seams [11]. Regrettably, due to paucity of works on CBM studies in Nigeria, there is currently no ongoing commercial production of CBM in the country.

Generally, these coals are mainly low ranked, sub-bituminous and bituminous in nature, with their occurrences reported in sedimentary basins in the northern, central and southern Benue Trough [10]. They occur at spatially at depths that exceed 400 m in the sub-surface [11–13]. Of these deposits, only the Enugu coal deposits have been exploited on a large scale, in particular, the Onyeama, Okpara and Milhouse/Awhum coal deposits. Only very little systematic exploitation is currently being conducted on the coal deposits in the Jangwa-Shankodi and Lafia-Obi areas (Fig. 1) [10, 11]. The coal measures, with an estimated proven reserve of about 128.3 million tonnes, are assigned to the Awgu Formation, a lagoonal to shallow marine/deltaic and predominantly shale-prone lithostratigraphic unit of Turonian to Coniacian age [13, 14]. For proprietary reasons, drill data from several wells showing a number of penetrated coal seams in Lafia-Obi, is under the custody of the National Steel Raw Materials Exploratory Agency (NSRMEA) in Nigeria. This data, showing a total of 34 encountered coal seams, is presented in the work of [9]. Previous studies on the Lafia-Obi and Jangwa-Shankodi coal deposits have, so far, mainly focused on the depositional environment, ultimate, proximate, rank, rheological, and thermal properties of the coals [9, 14–19]. Among these authors that have conducted studies on these coal deposits, the utilization potential of the coals has only received little attention. Moreover, the CBM potentiality of the coals, which requires adequate knowledge of the coal chemistry, is absent in previous literature. We have, therefore, for the first time in this area, estimated the gas content of coals within its geological formation as well as its potential for CBM production.

This study presents the results of coal chemistry of the Lafia-Obi and Jangwa-Shankodi coals, their utilization potential, and for the first time, an assessment of their CBM potential. The ultimate and proximate characteristics of the collected coal samples have been determined using established standard procedures whereas vitrinite reflectance (R_o (%)) and sorption capacity (cc/g) of the coals were estimated using empirical relations.

2 Geological setting

The formation of the south-eastern sedimentary basins in Nigeria is generally linked to the early Cretaceous break-up of the South-American and African tectonic plates [14, 20, 21]. The failed arm of the triple junction rift system led to the development of the Benue Trough and the associated intra-cratonic rift basins that make up the West and Central African Rift System (WCARS) (Fig. 2). The trough consists of several sub-basins and is broadly divided based on stratigraphy, geography and structure into three parts: the northern, southern and central Benue Trough respectively [22, 23]. The study area (Jangwa-Shankodi and Lafia-Obi) is located within the central section of the Benue Trough (Figs. 1 and 2).

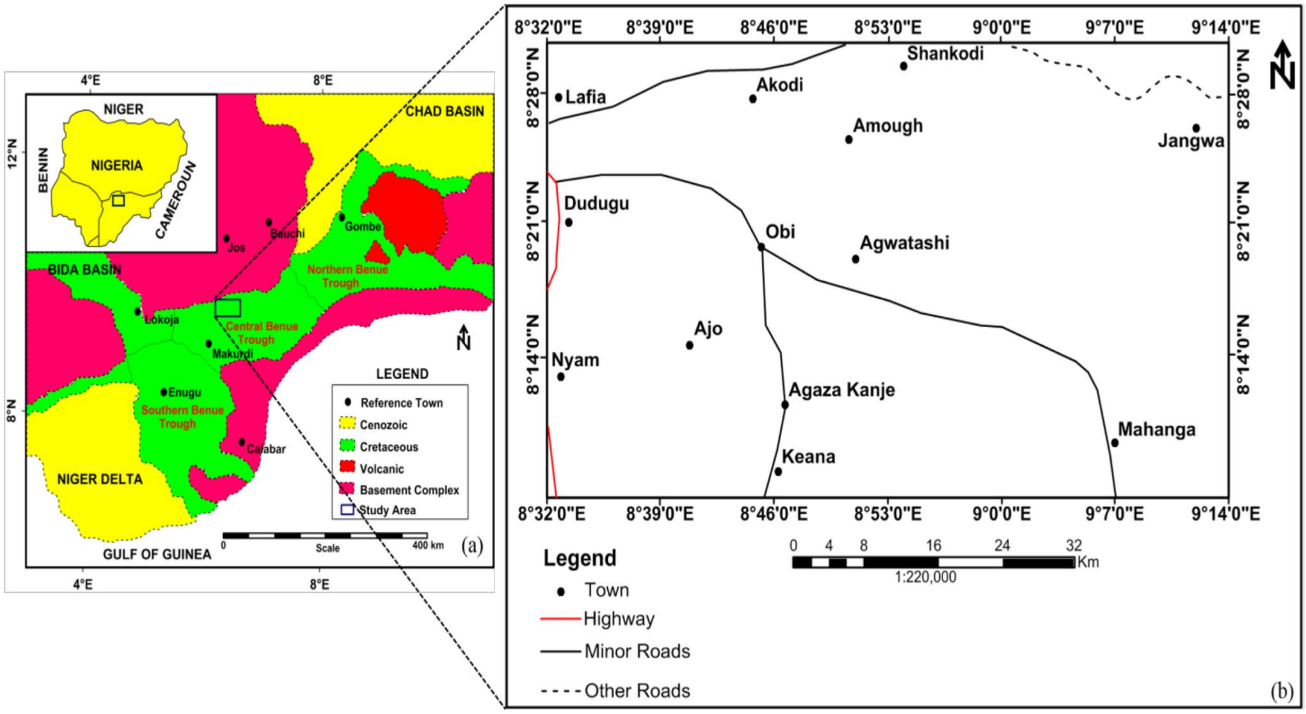


Fig. 1 **a** Outline geological map of southeastern, north-central and northeastern Nigeria showing the location of the central Benue Trough and study area (modified after [57]) **b** Enlarged view of the study area showing the various settlements within the Lafia-Obi and Jangwa-Shankodi localities

The cycles of sediment deposition within the Central Benue Trough comprises four stages which from youngest to oldest are: upper Campanian to Maastrichtian, upper Turonian to Coniacian, upper Cenomanian to middle Turonian, and middle Albian to middle Cenomanian [24] (Fig. 3). The coal-bearing Awgu Formation, which is of upper Turonian to Coniacian age, consists of thick and well-bedded shales that overlies the intensely fractured and jointed shale member of the Eze-Aku Group (Fig. 4). These shales, which are bluish-grey in color and can sometimes appear light or dark grey, have several coal seams of varying thicknesses and lengths interbedded within it [25] (Fig. 3). According to [26], the coal seams are mainly encountered along road cuts and river banks that are situated in the Obi and Shankodi areas of Nassarawa state, Nigeria (Fig. 5). This coal bearing formation is unconformably overlain by the Lafia-Wukari Formation [27].

3 Materials and methods

3.1 Collection of samples and laboratory procedure

A total of eight coal samples from the Awgu Formation were collected and obtained from and Lafia-Obi and Jangwa-Shankodi areas, Central Benue Trough in Nigeria where well cores have been previously drilled by the National Steel Raw Materials Exploration Agency (NSRMEA). Four coal samples each were marked; LAF – Lafia-Obi coal and JSK – Jangwa-Shankodi coal. The samples were further prepared using the guideline prescribed by BIS (British International Standard) in IS: 436 (Part 1/section 1)- 1964, which was applied in the work of [28].

3.2 Coal chemistry: proximate and ultimate analysis

Proximate and ultimate analysis describes the properties of the coal samples on the basis of their chemical constituents. These analyses are vital as they provide information that assist not only in the evaluation of the quality, rank and utilization potential of coals but also in the determination of their sorption capacities, which is essential in assessing the coalbed methane (CBM) gas potentials of coal deposits.

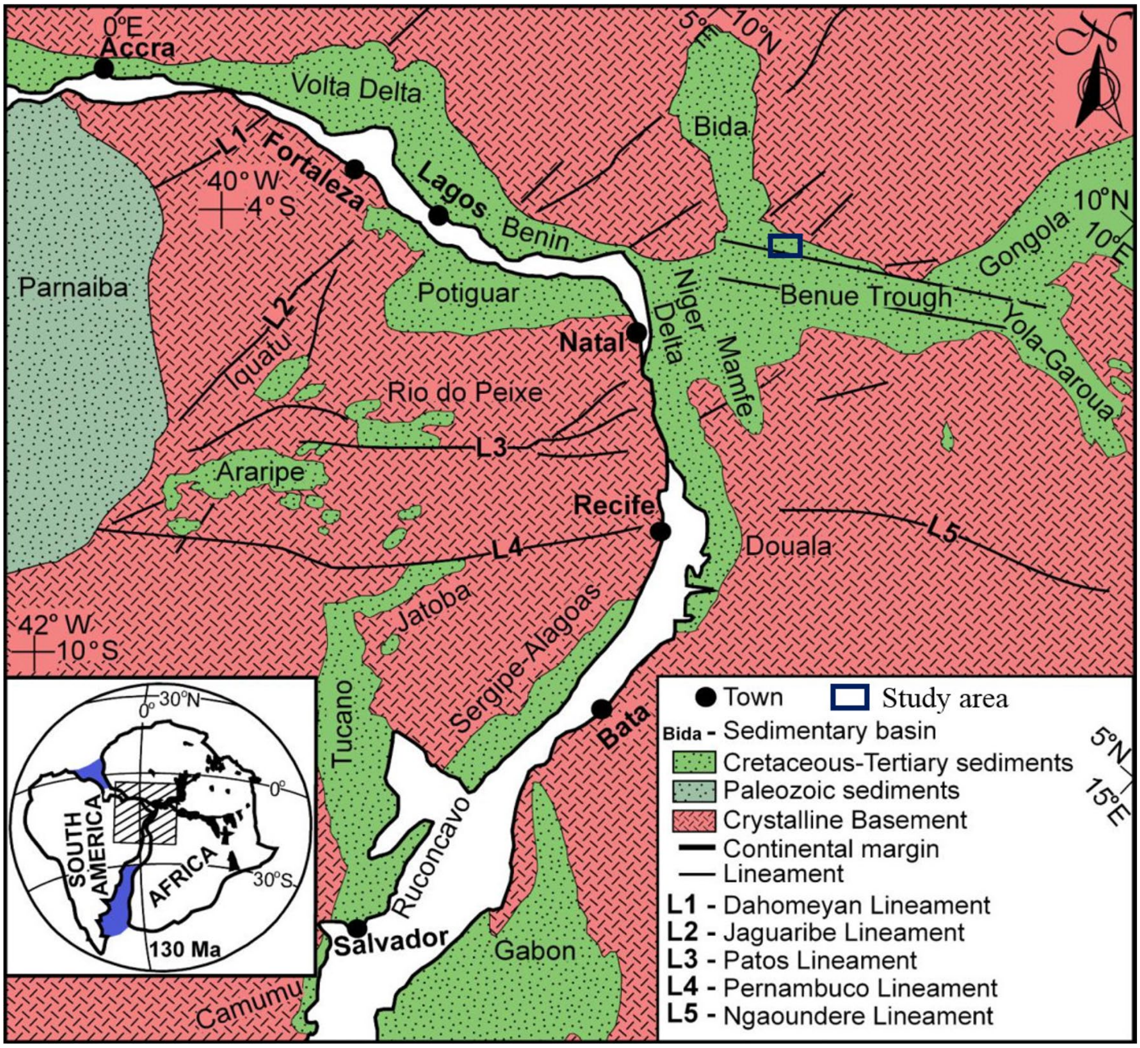


Fig. 2 Generalized geological map of a section of eastern West Africa showing the location of the study area (adopted from [58])

Specifically, proximate analysis reveals the coal quality in terms of inorganic and organic constituents. Volatile matter yield and fixed carbon comprises organic constituents whereas ash yield and moisture content are inorganic constituents. The coal heating values, moisture contents, ash and volatile matter (VM) yield were obtained in line with the guidelines specified by American Society for Testing and Materials (D3286, D3173, D3174, and D3175). Fuel ratio was determined as the ratio of fixed carbon and volatile matter yield. To obtain the fixed carbon, the percentages of ash yield, volatile matter (VM) yield and moisture content were deducted from 100. The heating values of the coals are given in British thermal unit per pound (Btu/lb).

Ultimate analysis provides the elemental make-up (nitrogen in weight percent, carbon, hydrogen, and sulphur) of the coal samples. Following the procedure outlined by the American Society for Testing and Materials (D3177, D3179, D3178), the elemental constituent of the collected coal samples were determined at the Geoscience Research Laboratory of the Nigerian Geological Survey Agency (NGSA) using the CHNS Euro EA Elemental Analyser. The total percentages of carbon, nitrogen, hydrogen, and sulphur were deducted from 100 to obtain the elemental oxygen content [9]. The results of these analyses were assessed to determine the suitability of the Lafia-Obi and Jangwa-Shankodi coals for methane gas production.

3.3 Coal rank

The maturity of coal, which steadily increases with the value of vitrinite reflectance, is generally determined by the coal rank [29]. This implies that vitrinite reflectance (R_o (%)) is a reliable parameter for rank determination of coal deposits. In the

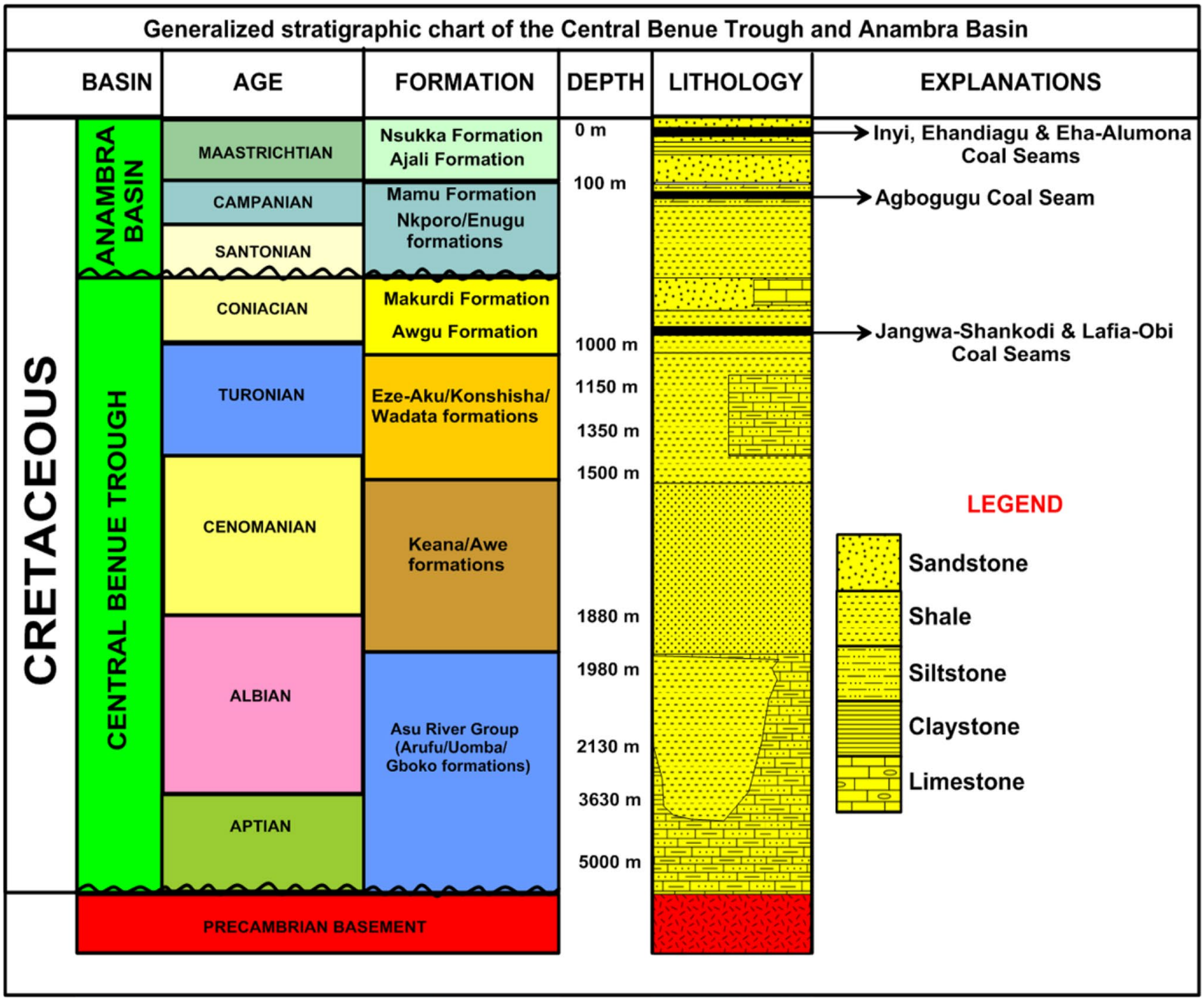


Fig. 3 Stratigraphic succession showing the sediments and coal seams of the Central Benue Trough and Anambra Basin (redrawn and modified after [59])

current study, R_o (%) was computed using the empirical relationship between vitrinite reflectance and volatile matter yield as expressed in [30] and given below:

$$R_o(\%) = -2.712 \times \log\left(\mathrm{VM}_{(\mathrm{daf})}\right) + 5.092 \tag{1}$$

where R_o (%) is vitrinite reflectance and $\mathrm{VM}_{(\mathrm{daf})}$ is volatile matter yield (dry ash-free basis) (%).

3.4 Determination of methane gas content of the coals

The internal surface of coal cleats bears most of the methane gas in coals in adsorbed condition. Previous investigators such as [28] and [31] have shown that the pressure and temperature of coals varies directly and inversely, respectively, with the sorption capacity of coals. A more general estimate of the volume of absorbed gas (G_{saf}), which shows the relationship between G_{saf}, depth, pressure, and proximate analysis parameters, have been proposed by [32] and is given below:

$$Gsaf = \left(\frac{100 - M - ASH}{100}\right)(0.75)\,K_o(0.096h)^{n_o} - 0.14\left(\frac{1.8h}{100} + 11\right) \tag{2}$$

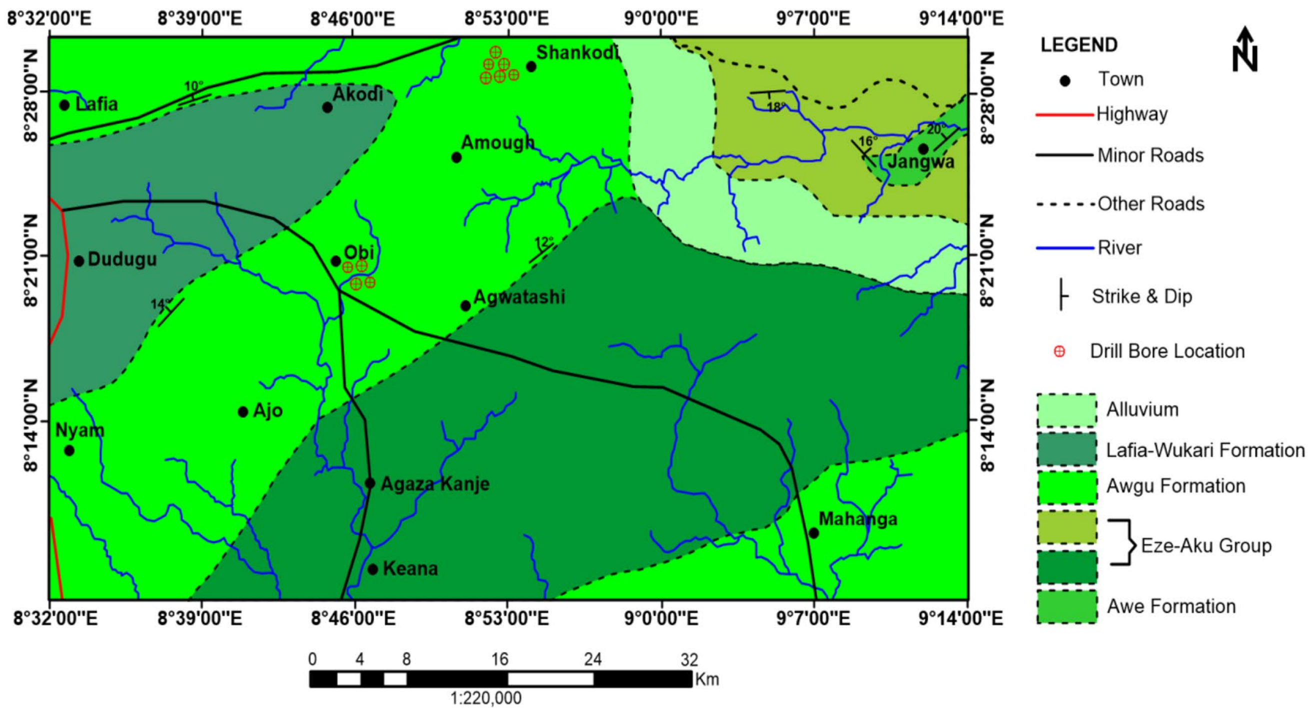


Fig. 4 Geological map of the study area showing the locations of drill bores within the Awgu Formation

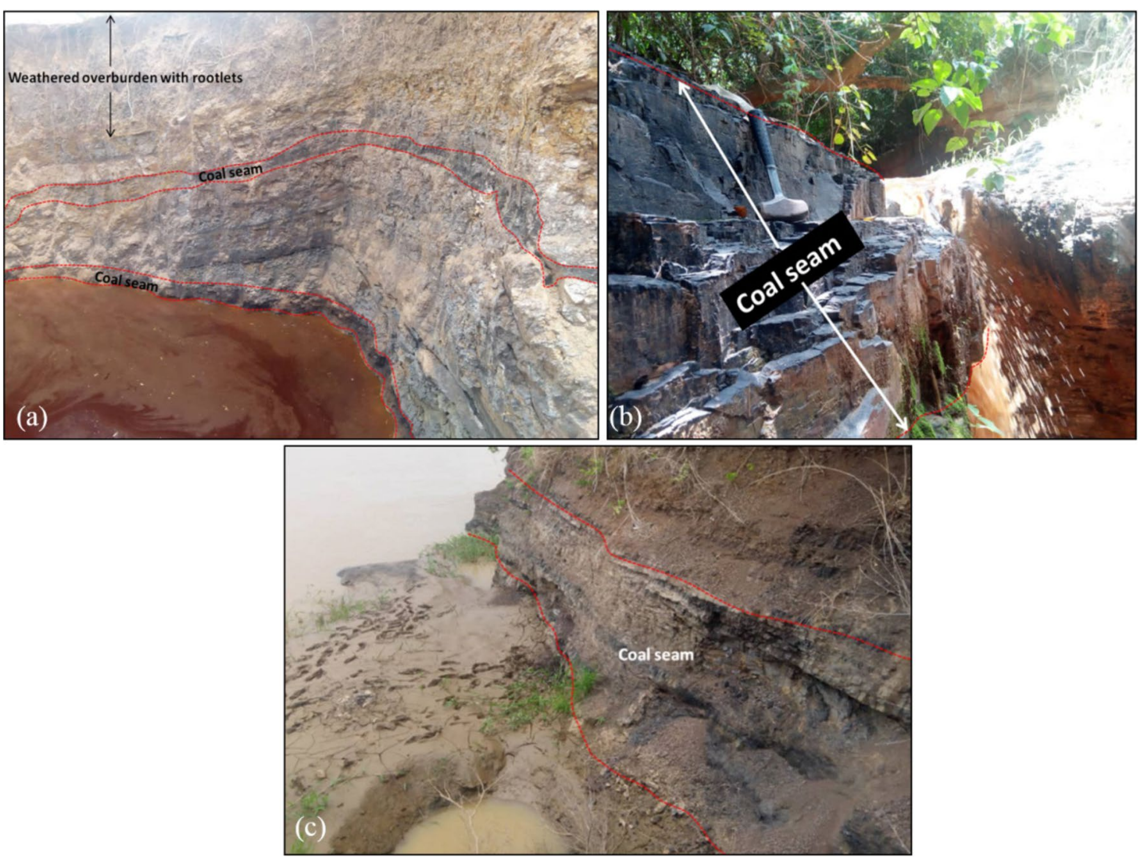


Fig. 5 **a** Outcrop photograph showing coal facies observed at an artisanal mining site in Shankodi **b** Outcrop photograph of silty-sandstone facies associated with a coal seam in Lafia-Obi **c** Outcrop section showing a coal seam encountered along River Dep in Shankodi

where ASH is ash content (%), M is moisture content (%), h is depth of sample (m), and G_{saf} is dry, ash free gas storage capacity (cc/g), and $n_o$is a constant, which is stated as:

$$n_o = 0.315 - \frac{0.01FC}{VM} \tag{3}$$

where *FC* is fixed carbon (dry ash-free basis) (%), *VM* is volatile matter yield (dry ash-free basis) (%).

$$K_o,\ \text{in cubic centimeters per gram per atmosphere} = \frac{0.8\text{FC}}{\text{VM}} + 5.6 \tag{4}$$

$$P,\ \text{pressure at depth, h} = \text{hydrostatic pressure in atmosphere}, P_{\text{hyd}} = 0.096 \times \text{h} \tag{5}$$

4 Results and discussion

4.1 Analysis of coal quality

The results of proximate analyses show that the fixed carbon contents, which is a major determinant of coal maturation ranges from 55.97 to 56.30% (Table 1). These values indicate that the coal samples are moderately mature. According to [33] and [34], coals with fixed carbon content that varies between 45 and 85% are of moderate quality and maturity. At greater depths, the fixed carbon content of coals usually shows an increasing trend [35]. This is clearly observed in Fig. 6. The Lafia-Obi coals (LAF), which occur at slightly greater depths, indicate higher values of fixed carbon compared to their Jangwa-Shankodi (JSK) counterpart. The greater depth interval of the Lafia-Obi coals, which yielded higher values of fixed carbon, are most likely to yield higher values of gas contents compared to Jangwa-Shankodi (JSK) coals. Basically, bituminous and sub-bituminous coals that undergo deeper burials are known to have greater gas contents [11, 36]. Similarly, the volatile matter yields and moisture contents which ranges from 29.98–30.34% to 2.28–2.56%, respectively are moderate in value [37] (Table 1). The values of ash yield (7.83–8.64) exhibited by the studied coals are within the range of a good quality coal (< 10%) [9]. Fuel ratios of the coal samples are generally low (1.72–1.87) and showed less variation [29] (Table 2). Closely similar values of fuel ratios were obtained in the bituminous Bapung and Tikak Parbat coal deposits in India, which showed good potentials for CBM production [28].

The elemental composition of hydrogen, carbon, oxygen, sulphur, and nitrogen in the studied samples are displayed in Table 2. Here, the percentage of carbon is observed to vary between 52.92 and 54.5% with the Lafia-Obi coals (LAF) showing slightly higher values than the Jangwa-Shankodi coals (JSK). Oxygen and hydrogen contents, which ranges from 3.07–6.92% to 3.89–4.55%, respectively are low to moderate while nitrogen contents are generally very low [33] (Table 2). These show good prospects for coals that are viable for CBM production. More so, sulphur, an undesirable element in coal, is generally low (< 1) [33]. In this case, the Lafia-Obi coals (LAF) possess lower quantities of sulphur than the Jangwa-Shankodi coals (JSK) and is therefore of better quality than it.

Table 1 Results of proximate analysis (air dried basis) of the coals

Sample no	Depth (m)	Moisture content (wt %)	Ash yield (wt %) (dry basis)	Volatile matter yield (wt %) (dry ash-free basis)	Fixed Carbon (wt %)
JSK 1	15.00	2.34	8.64	30.26	56.09
JSK 2	16.50	2.37	8.48	30.34	56.08
JSK 3	17.70	2.56	7.99	29.99	56.14
JSK 4	18.10	2.33	8.49	30.21	55.97
LAF 1	19.00	2.28	7.83	30.20	56.20
LAF 2	20.20	2.45	8.34	29.98	56.18
LAF 3	21.50	2.48	7.94	30.00	56.21
LAF 4	23.00	2.39	8.29	30.22	56.30

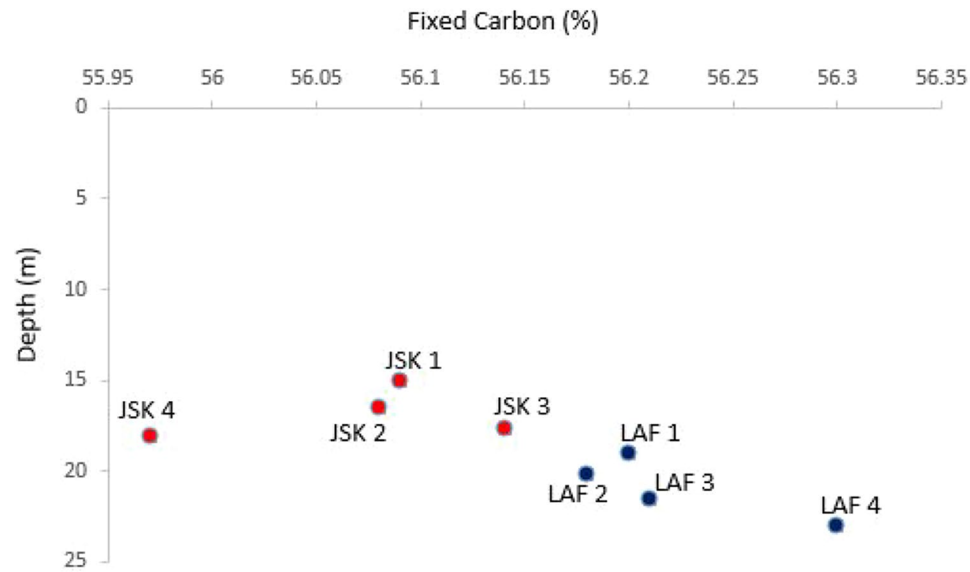


Fig. 6 Scatter graph showing variation in fixed carbon of the studied coals with depth

H/C ratio varies from 0.072 to 0.086 while O/C ratios range from 0.058 to 0.128. The van Krevelen diagram, which shows the chemical variation of coal macerals and kerogen, is shown in Fig. 7. In the current study, kerogen lies in the Type IV zone, which suggests the generation of methane gas by the studied coal samples. According to [38], when H/C ratio is below 0.5 (as in this case), the residual kerogen are only capable of expelling methane gas. Also the estimated range of vitrinite reflectance which varies between 1.073% and 1.087% indicates thermogenic gas expulsion in the coals [38]. These results are an indication of the high CBM prospecting potential of the coal seams in the study area. From the results obtained, an increase in coal maturity and depth corresponds to an increase in gas content (Table 2; Figs. 2 and 9).

These results of proximate and ultimate analysis show reasonable agreement with the sub-bituminous and bituminous coal-types of the Wyodak-Anderson Cretaceous coals in the Powder River Basin, U.S.A where methane gas is currently being exploited [39]. Such bituminous type-coals are good candidates for CBM production ([28, 36] p. 2633). This is because they are deeply buried, and characterized by high reservoir pressure, high permeability and high gas content [28, 38].

4.1.1 Heating values of the studied coals

The calculated heating values of Jangwa-Shankodi coals and Lafia-Obi coals varies between 12,319.5 and 12,353.9 Btu/lb, and 12, 341.0 and 12,366.8 British thermal unit per pound, respectively (Fig. 8). These figures represent the total heat (energy) content of the coals after combustion. JSK 3 and JSK 4, with the lowest values of heat generation (12336.7 Btu/lb and 12319.5 Btu/lb), will most likely generate the least heat after combustion. On other hand, the Lafia-Obi coals, especially LAF 1 and LAF 2, will produce the greatest heat on combustion due to their higher heating values (12, 366.8 Btu/lb).

Heating values of coal samples are oftentimes affected by the coal moisture contents and ash yields [37]. Visual correlation of the ash contents of the coals against their individual heating values indicate that (to a reasonable level) coals with higher heating values possess lower ash yields and vice-versa (see Table 1 and Fig. 8). The Jangwa-Shankodi coals, which have lesser heating values possess relatively higher ash yields. Thus, higher ash yields of coals results in decreased coal quality. Conversely, the comparatively lower ash yields of the Lafia-Obi coals are mainly responsible for the slightly higher heating values of the coal samples (Table 1, Fig. 8). According to [9], lower ash yield and higher carbon improve coal reservoir porosity, which results in better methane absorption capacity. Therefore, the Lafia-Obi coals, which possess lower ash yields and higher fixed carbon will absorb greater volume of methane compared to the coals from the Jangwa-Shankodi area.

4.2 Rank of the studied coals

Vitrinite reflectance (R_o (%)) is a trend tool that is commonly used to decipher coal rank and/or maturity [28]. In this study, the vitrinite reflectance values of the coal samples ranges from 1.073 to 1.087% with LAF 2 showing the highest

Table 2 Results of ultimate analysis (air dried basis) and other coal parameters

Sample no	Depth (m)	Carbon (wt %)	Hydrogen (wt %)	Oxygen (wt %)	Nitrogen (wt %)	Sulphur (wt %)	Fuel ratio	H/C ratio	R_o (%)	O/C ratio	Kerogen TyKerogen type
JSK 1	15.00	53.17	4.55	3.07	1.23	0.11	1.85	0.086	1.076	0.058	IV
JSK 2	16.50	53.19	4.49	3.80	1.22	0.14	1.72	0.084	1.073	0.071	IV
JSK 3	17.70	52.92	4.47	3.68	1.20	0.11	1.87	0.085	1.086	0.070	IV
JSK 4	18.10	53.16	4.53	3.81	1.19	0.12	1.85	0.085	1.078	0.072	IV
LAF 1	19.00	54.30	4.06	6.87	1.34	0.08	1.86	0.075	1.078	0.127	IV
LAF 2	20.20	54.35	3.89	6.79	1.40	0.09	1.87	0.072	1.087	0.125	IV
LAF 3	21.50	54.52	3.95	6.90	1.36	0.13	1.87	0.072	1.086	0.127	IV
LAF 4	23.00	53.99	3.90	6.92	1.38	0.10	1.86	0.072	1.077	0.128	IV

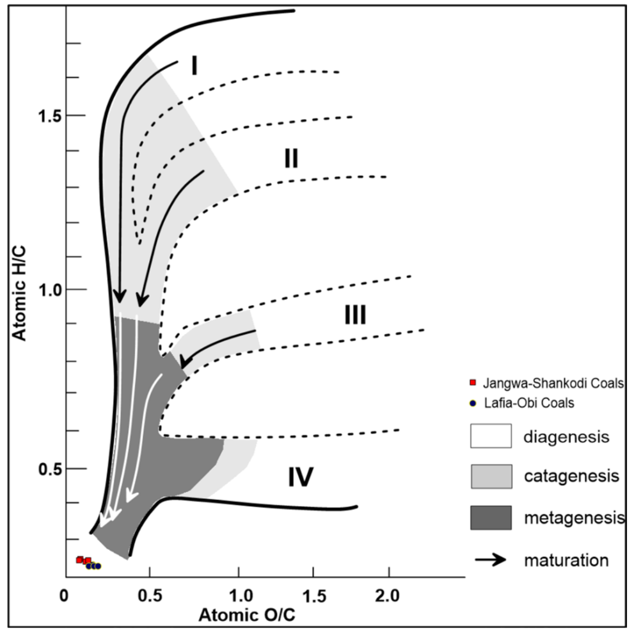


Fig. 7 van Krevelen type diagram showing the distribution of kerogen types in relationship with the O/C and H/C atomic ratios for all the coal samples (adopted and re-drawn from [38])

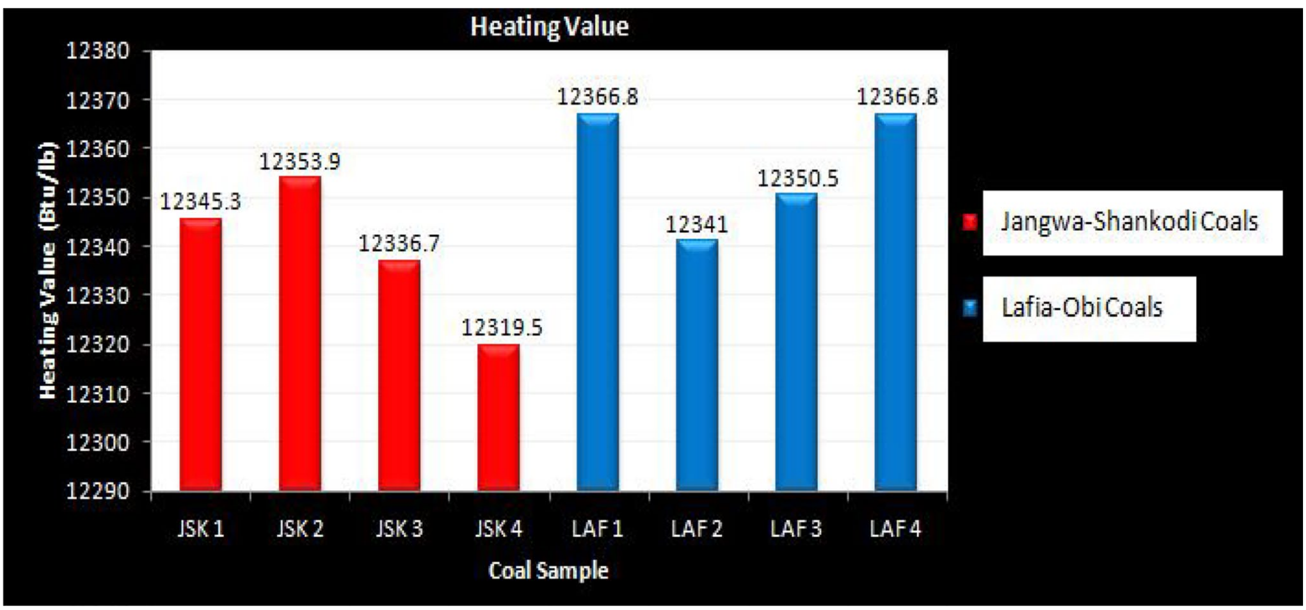


Fig. 8 Bar chart showing the computed heating values of the studied coals

value at a depth of 20.20 m (Table 2). According to the rank parameters discussed by [37, 40, 41], these values suggests that the coal samples belong to the medium-volatile bituminous rank, which is in agreement with the bituminous classification reported in previous studies [9, 42]. The plot of coal rank classification established by the United States Geological Survey (U.S.G.S) and presented in the work of [43] showed remarkable agreements with rank results from vitrinite reflectance. According to the plot, all the studied coals fall within the medium volatile bituminous rank with under the high-volatile C category (Fig. 9).

There is a noticeable increase in vitrinite reflectance value with depth (Fig. 10, Table 2). Similar observations have been reported in the Pochontas coal field in Tazewell and McDowell County in Virginia, U.S.A, the Moranbah Coal Measures in Australia, and the German Creek Coals where methane gas occurrence has been confirmed [44, 45]. A

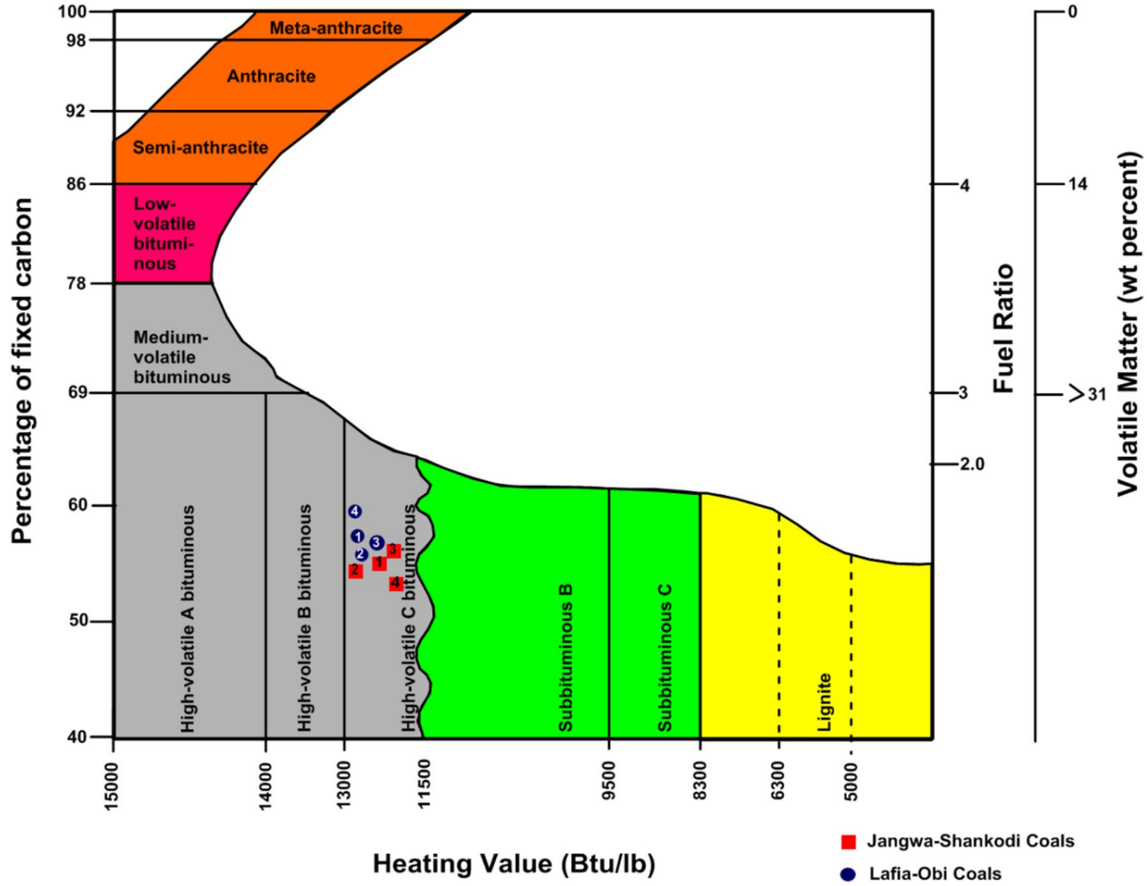
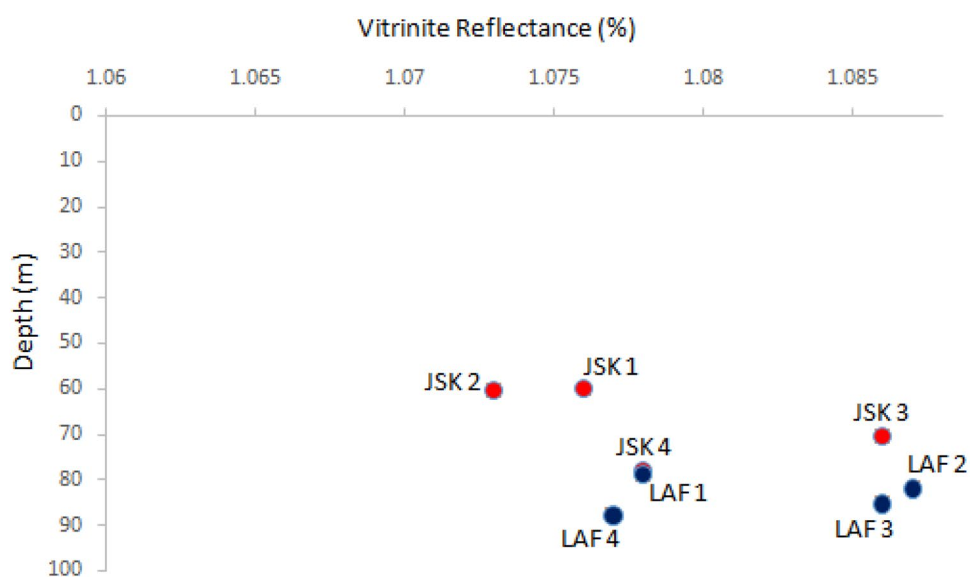


Fig. 9 Diagram showing classifications of the studied coals by ranks (modified after [43])

Fig. 10 Scatter graph showing variation in vitrinite reflectance of the studied coals with depth



review of previous studies on coal reveals several reports that show increases in vitrinite reflectance and fixed carbon with depth, and a reduction in the value of volatile matter yield with depth [12, 37, 45, 46]. The increase in these coal parameters with depth is indicative of good quality coal that shows huge prospects for methane gas accumulation.

4.3 Industrial applications of the studied coals

Although the coal samples showed moisture content values that are slightly higher than that stipulated for coke making, they had acceptable values of volatile matter for metallurgical coke production [47, 48]. However, the Lafia-Obi coals (LAF), which showed higher carbon contents, would be preferred for coke formation [49]. This makes the Lafia-Obi coals (LAF) more suitable for coke production compared to the Jangwa-Shankodi coals (JSK).

All the coal samples have heating values that are suitable enough for power generation [12]. The Jangwa-Shankodi coals (JSK) with lower fuel ratios and higher volatile matter could function optimally during power generation and heat production. The lower sulphur contents of the Lafia-Obi coals (LAF) make them more suitable for heating of residential buildings, firing kiln for cement production, foundry coke production, and smokeless fuel production without any concern for sulphur pollution. The coal samples are also suited for liquefaction because high-volatile bituminous, sub-bituminous and lignitic coals are potentially good for liquefaction to produce tar and synthetic crude oil [48].

For coal gasification, the coal samples, being bituminous have potentials for hydro-gasification to produce methane [48].

4.4 Estimated gas content of the coals

The estimated adsorbed gas content of the coals as determined from Eq. 2 is given in Table 3. The gas contents of the studied coals range from 12.65 to 13.20 cc/g. These values are consistent with coals that show good potentials for methane gas occurrence [50]. Moreover, the range exceeds the benchmark value of 8.5 cc/g, which is recommended for economic viability of coalbed methane [28, 51]. Although all the coal samples appear suitable for commercial exploitation of CBM, the Lafia-Obi coals (LAF) were characterized by higher values of adsorbed gas compared to the coals from the Jangwa-Shankodi area (JSK) (Table 3). This could be attributed to its higher fixed carbon content (which suggests greater maturation and better quality), which is as a result of deeper burial (see Fig. 6).

4.5 Linear correlation of coal parameters and gas content

In this current study, statistical methods are used to establish a correlation between the gas contents of the coals and their proximate and ultimate characteristics. Ash yield and moisture content are known to adversely affect the capacity of coals to absorb methane [52]. According to [26], 5% and 1% of a coal's moisture content reduces its sorption capacity by 65% and 25%, respectively. Figure 11 shows a similar trend where an increase in ash and moisture fraction resulted in a decrease in gas sorption capacity of the coal samples.

Conversely, studies on U.S coal classification showed that the gas content of coals increases progressively with increase in fixed carbon content [32]. A similar observation has also been made in this study (Fig. 12a).

Results of ultimate parameters also clearly show an increase in gas content with carbon (see Fig. 12c). This positive correlation between gas content and carbon content suggests a preference for the Lafia-Obi coals (LAF) over the

Table 3 Estimated gas storage capacity of the studied coals

Sample no	Depth (m)	n_o	K_o	P (atm.)	Gas storage capacity (cc/g)	Ash + moisture content (fraction)
JSK 1	60.00	0.29646	7.08288	5.7600	12.65	0.110
JSK 2	60.50	0.29652	7.07871	5.8080	12.73	0.109
JSK 3	70.60	0.29628	7.09757	6.7776	12.72	0.106
JSK 4	78.10	0.29647	7.08216	7.4976	12.66	0.108
LAF 1	79.00	0.29639	7.08874	7.5840	13.20	0.101
LAF 2	82.20	0.29626	7.09913	7.8912	13.10	0.108
LAF 3	85.50	0.29626	7.09893	8.2080	13.16	0.104
LAF 4	88.00	0.29637	7.09040	8.4480	13.11	0.107

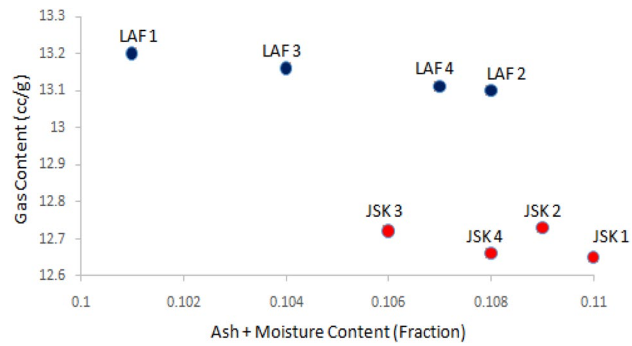


Fig. 11 Graphical relationship between coal gas contents and (ash + moisture) fractions

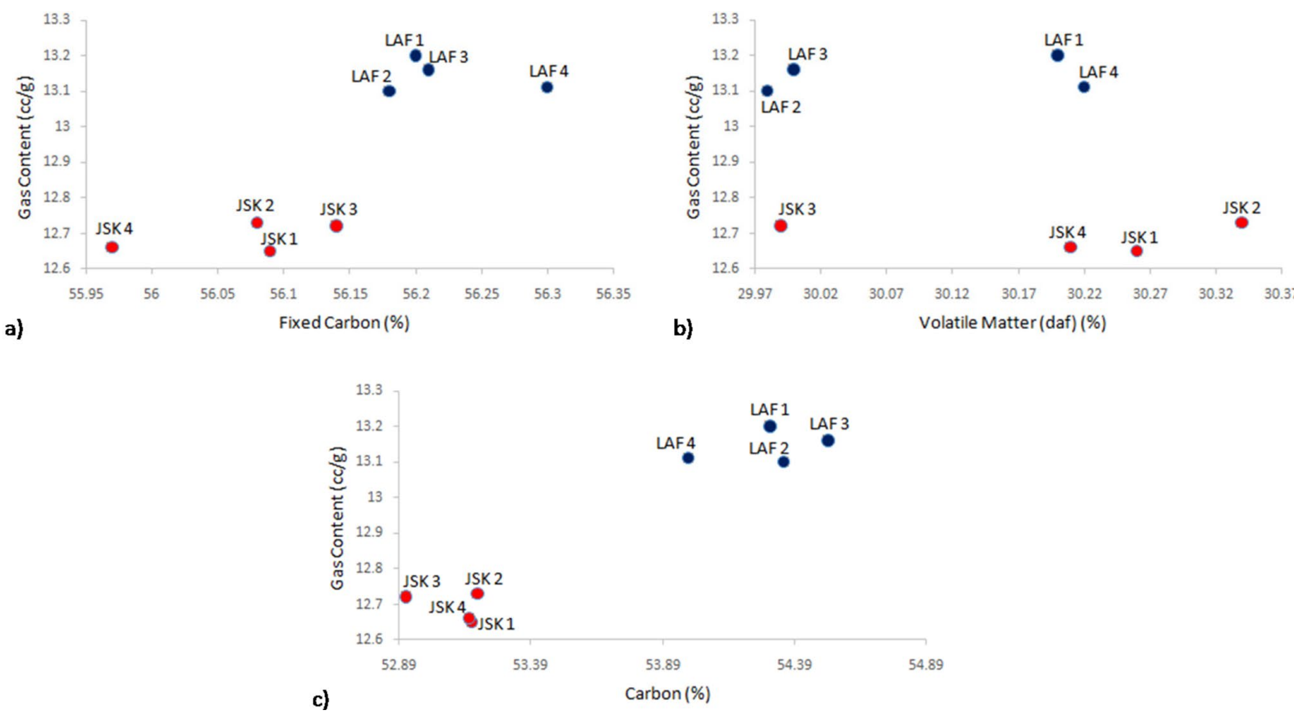


Fig. 12 Graphical representation of the variation in gas content of the studied coals with **a** fixed carbon **b** volatile matter yield **c** carbon percentage

Jangwa-Shankodi coals (JSK) for CBM production. The relatively lower values of volatile matter yield exhibited by the Lafia-Obi coals (LAF) also strengthens this argument (Fig. 12b) since gas content increases with decrease in volatile matter yield [53].

Relatively higher R_o (%) values, which was a function of increased carbon content and greater burial depth resulted in increase in gas content of the coal samples (Fig. 13a, b).This is in agreement with the findings of [54–56]. Basically, an increase in burial depth leads to an increase in temperature and pressure which enables plant materials to undergo coalification in anoxic condition. As a result, the coals become progressively enriched in carbon while continuously expelling volatile matter [28]. This leads to a progressive increase in methane content, which is adsorbed on the cleats of the coal as burial depth increases. Thus, the adsorption capacity of the coal is enhance [57].

Based on the correlation of coal properties with gas content, it is therefore plausible to conclude that the studied coals possess good potentials for CBM production with the Lafia-Obi coals (LAF) showing better prospects than the Jangwa-Shankodi coals (JSK). To ameliorate the drawback associated with empirical estimation, core drilling technology should be employed to ascertain the insitu volume of methane absorbed by the coals and hence, verify the empirical estimates of CBM reported in this study.

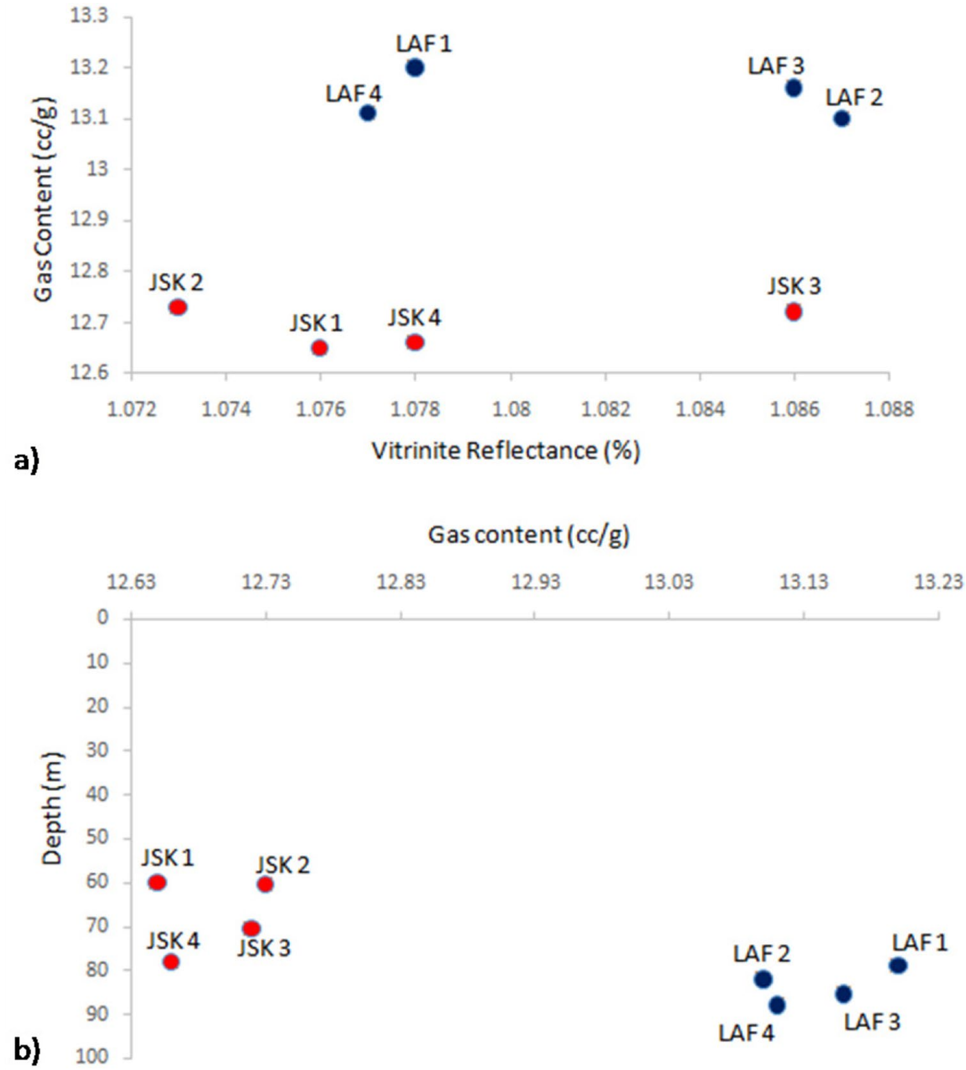


Fig. 13 Variation in gas content of the studied coals with **a** vitrinite reflectance **b** depth

5 Conclusion

The chemistry of Lafia-Obi and Jangwa-Shankodi coals (Central Benue Trough, Nigeria) using ultimate and proximate analyses have been carried out to determine the coals utilization potentials as well as assess their suitability for coalbed methane (CBM) production. The analyzed coal samples showed that:

1. The volatile matter yield, fixed carbon, moisture and ash contents of the Lafia-Obi and Jangwa-Shankodi coals range from 29.99–30.34% and 29.98–30.22%, 55.97–56.14% and 56.18–56.31%, 2.33–2.50% and 2.28–2.40% and 7.99–8.64% and 7.83–8.34%, respectively.
2. In the same order as in (1) above, the percentage ranges of elemental hydrogen and carbon are 4.47–4.55% and 3.89–4.06% and 52.92–53.19% and 53.99–54.52%. Sulphur content was lower in the Lafia-Obi coals (0.11–0.14%). The gas contents of the studied coals range from 12.65 to 13.20 cc/g
3. These coals can find industrial applications for heating of residential buildings, firing kiln for cement production, power generation, liquefaction, foundry coke production, and smokeless fuel production without any significant concern for sulphur pollution.
4. The coals, which are of medium-volatile bituminous rank, is composed of methane gas-generating kerogen (Type IV). Further, the coals revealed a generally H/C ratio that is < 0.5, which is typical of methane-generating coal deposits.

5. The estimated range of vitrinite reflectance which varies between 1.073% and 1.087% indicates thermogenic gas expulsion in the coals.
6. These values are consistent with coals that show good antecedents for CBM production.

Acknowledgements Prof. Usman Onoduku of the Department of Geology, Federal University of Technology, Minna and Prof. Ifeanyi Oha of the Department of Geology, University of Nigeria, Nsukka, are acknowledged for their technical inputs, which improved the quality of the manuscript.

Author contributions COE, IME and JOA conceptualized the study and along with IGU, participated in data curation, formal analysis, and data interpretation. UKO provided immense technical support. COE drafted the manuscript.

Funding No funding was received for conducting this study.

Data availability Data used in this study can be provided by the corresponding author on reasonable request.

Code availability Not applicable.

Declarations

Competing interests The authors have no competing interests to declare that are relevant to the content of this article.

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