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ORIGINAL RESEARCH ARTICLE

CHARACTERISATION OF BENUE TROUGH COALS FOR EFFICIENT UTILISATION

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ABSTRACT

Nigeria is Africa's largest economy, and coal is the country's most abundant fossil fuel. Its utilisation in Nigeria faces significant challenges due to limited data on its characterisation and properties. The research looks at the physicochemical, mineralogical, functional groups, and thermogravimetric properties of three Nigerian coals—Gombe coal, Kogi coal, and Lafia-Obi coal—using X-ray Diffraction (XRD) to examine their morphological structures, FTIR spectroscopy to identify the functional groups and cross-linked molecules, and Thermogravimetric Analysis (TGA) to monitor the changes in sample weight with time and temperature. The mineralogical analysis showed that graphite, quartz, and goethite are present in all three of the coals examined. Orthoclase is found in both the Gombe and Kogi coals, while microcline is only present in the Lafia-Obi coal. Moreover, anatase is also found in Gombe coal. Interestingly, since it has a high sulphur content (0.83%), low aromatics, a high oxygen content (5%), and minerals such as anatase (0.96%) and orthoclase (10%), this coal is not suitable for coke production. On the other hand, the Kogi coal was found to contain a high amount of fixed carbon (52.40%), have low sulphur (0.23%), and possess prominent graphite, which means it can be used for coking when blended. Furthermore, it was noted that Lafia-Obi coal is the most appropriate for coking, as it has a high fixed carbon content (56.40%), low moisture (2.96%), a high aromatic content, and contains the minerals graphite, quartz, and microcline. Hence, this study presents important insights into the characteristics of coals widely available in Nigeria and could help support industrial applications and more efficient use.

1.0 Introduction

Energy is mainly obtained from fossil fuels, such as coal (Hu *et al.* 2026; Isah *et al.* 2026; Sun *et al.* 2024). Even though there are continued worries about climate change, global warming, and environmental degradation, coal has continued to play an important role in the sustainable development of many countries (Zhang *et al.* 2024). The present worldwide focus on alternative energy sources has once again sparked interest in coal production, particularly in view of the geopolitical tensions and supply disruptions caused by the ongoing conflict between Ukraine and Russia (Isah *et al.* 2025; World Energy Outlook 2024; Isah, 2023) and the recent intensification of hostilities in the Middle East.

The US Energy Information Administration estimates that the world's coal reserves total 926 gigatonnes (Gt), with substantial deposits found in China, the United States, India, Australia, Indonesia, Russia, and Germany (Akinyemi *et al.* 2020). In Nigeria, coal was of great importance to economic development until oil was discovered in 1956 at Oloibiri in Bayelsa State (Fatoye and Gideon, 2013). Although coal had been the country's first resource to be explored for energy, production has since fallen to negligible levels from a peak of about 1 million tonnes in 1959 (Denloye and Akinola, 2016). Akinyemi *et al.* (2020) state that Nigeria's known coal reserves are about 639 million tonnes (Mt), most of which are situated in the sedimentary basin known as the Benue Trough. Nigeria is the country in Africa with the second-largest coal reserves, these being estimated at 4 billion tonnes (Nyakuma and Jauro, 2016). In the end, oil became the main source of revenue for the nation, making up around 80% of its annual income (Adebesin and Amosun, 2022).

Coal is made up of fused aromatic clusters (Sonibare *et al.* 2010). Nevertheless, its properties are due to its complex composition and structure, a factor that affects the way it is processed and used (Isah *et al.* 2025; Shang *et al.* 2025). It is essential to have a thorough understanding of coal structure if it is to be efficiently used in carbonisation, gasification, liquefaction, and combustion (Yan *et al.* 2020). The proposed change provides promising prospects for progressing clean coal technologies and for achieving sustainable utilization (Nyakuma and Jauro, 2016). Investigating and developing the nation's natural coal reserves could help to diversify Nigeria's economy and allow for a gradual shift from its present petroleum-based industry and technology sector. Moreover, important analytical techniques such as FTIR, TGA, and XRD have been used to characterise coal and other solid fuels. For example, FTIR provided information about the cross-linked molecules in organic materials and the functional moieties (Isah *et al.* 2026; Isah *et al.* 2025; Adebesin and Amosun, 2022; Yan *et al.* 2020; Sonibare *et al.* 2010).

Fatoye and Gideon (2013) examined the economic geology of coal resources in Nigeria and looked at the various ways in which coal can be used, such as by liquefaction, combustion, gasification, coke-making, and in other industrial capacities, without, however, describing any of the Nigerian coals. The present study involves the characterisation of three samples of Nigerian coal obtained from the Benue Trough (from Gombe, Kogi, and Lafia-Obi) by means of FTIR, TGA, and XRD analytical techniques and also evaluates their suitability for efficient use in Nigeria through combustion, liquefaction, gasification, and carbonisation.

2. Materials and Method

2.1 Samples Collection and Preparation

Three Nigerian coal samples were analysed in this study. As shown in Figure 1, the samples were collected from three locations within the Benue Trough: Gombe, Kogi, and Lafia-Obi. Samples were initially crushed (<150 μm) using a mortar and pestle. For the FTIR analysis, samples were blend with KBr at a 1:100 ratio and pressed into pellets. For the TGA analysis, about 10-15 mg of the coal sample was placed in an alumina crucible, while a powdered sample was prepared for the XRD analysis.

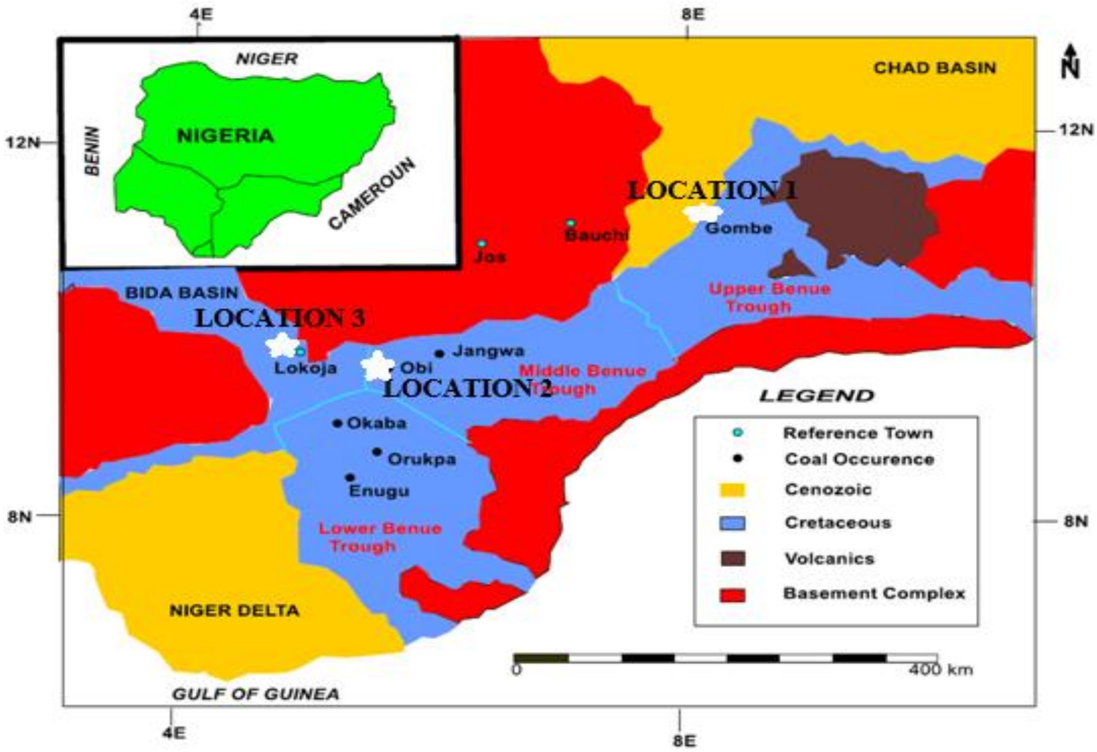

Figure 1: An adapted and modified map of the coal deposits (Mangs *et al.* 2022; Akinyemi *et al.* 2020; Obaje *et al.* 1999).

2.2 Samples Characterisation

2.2.1 Proximate and ultimate analyses

The proximate analyses were determined in accordance with ASTM D3172-13, while the ultimate analyses were determined in accordance with ASTM D3176-15 (Garba *et al*. 2016).

2.3 Samples Analyses

This study used TGA, FTIR, and XRD to characterize three coal samples.

2.3.1 FTIR spectroscopy

The FTIR spectra obtained were recorded in transmittance mode (T, %), with 20 scans from 400-4000 cm^{-1} at a resolution of 4 cm^{-1}, using a Perkin-Elmer System-2000 FTIR spectrometer (USA).

2.3.2 Thermogravimetric analysis (TGA)

The three coal samples were analysed by TGA. In an alumina container, 10–15 mg of sample with (<150 µm) was heated under an inert atmosphere using a (TGA 4000 PerkinElmer, Netherlands).

2.3.3 X-ray diffraction (XRD)

Thin-film samples were examined using a Thermo Scientific ARL X'TRA X-ray diffractometer manufactured in Switzerland with Cu radiation (wavelength = 0.15418 nm). Scanning was done at 2° per minute from 10° to 70° with a step size of 0.02°. A voltage of 40 kV and a current of 40 mA were used.

3. Results and Discussion

3.1 Sample Properties

The properties of samples are presented in Table 1. For example, the Kogi sample has the greatest moisture content at 11.97%, whereas the Lafia-Obi sample has the lowest at 2.96%. The Lafia-Obi sample also has the highest ash content at 13.41%, the Kogi sample having the lowest at 6.40%. With regard to sulphur content, the Gombe sample has the highest at 0.83% and the Kogi sample the lowest. Furthermore, the Lafia-Obi sample has the highest carbon content at 70.63% when compared with the other two samples.

Table 1: Samples proximate and ultimate properties

Parameter	**Samples**		
	Gombe	**Kogi**	**Lafia-Obi**
Moisture	9.09	11.97	2.96
Ash	7.79	6.40	13.41
Volatile Matter	28.25	29.26	27.28
Fixed Carbon	54.87	52.40	56.40
Carbon	68.37	69.51	70.63
Hydrogen	1.11	1.08	1.03
Nitrogen	0.63	0.94	0.52
Sulphur	0.83	0.23	0.72
Oxygen	5.00	4.30	7.00

3.2 FTIR Results Discussion

The FTIR results are presented in Figure 2. The peaks at 3190 and 3205 cm^{-1} are characteristics of aromatic C-H stretching modes, revealing aromatic ring structures in the coal. Additionally, the peaks at 2847 and 2914 cm^{-1} suggest the presence of aliphatic and alicyclic C-H bonds (CH_3, CH_2 and CH groups), likely associated with alkyl side chains or aliphatic components (Akinyemi *et al.* 2021). However, the peaks at 1580 and 1595 cm^{-1} are indicative of the stretching modes of aromatic C=C bonds, further confirming the presence of aromatic ring structures, and also correspond to C=O asymmetric stretching vibrations, implying the existence of carbonyl groups in ketones, aldehydes, or carboxylic acids (Isah *et al.* 2024). The peak at 1438 cm^{-1} is likely due to bending modes of CH_3 and CH_2 groups while the peak at 1170 cm^{-1} is indicative of C-O stretching vibrations, possibly from ether or ester groups. It is also noteworthy that the peak at 1222 cm^{-1} is often indicative of C-OH bending in phenolic, carboxylic acid groups, or esters. Aromatic C-H out-of-plane deformation vibrations are characterised by the peaks at 693, 745, and 909 cm^{-1}, respectively (Isah *et al.* 2024).

Furthermore, it was observed that Gombe coal has low aromatic and moderate aliphatic content, with high oxygen content while Kogi coal has high aromatic content, moderate aliphatic hydrocarbons, and high oxygen. Lafia coal on the other hand has high aromatic and moderate aliphatic hydrocarbons, with low moisture content. It is clear from the results that Gombe coal is found to be unsuitable for coke production due to its significant oxygenated groups and low aromatics. Conversely, Lafia-Obi coal is observed to be best suited for coking due to its high aromatic content, which helps form a strong coke structure during carbonisation, while moderate aliphatic content provides plasticity.

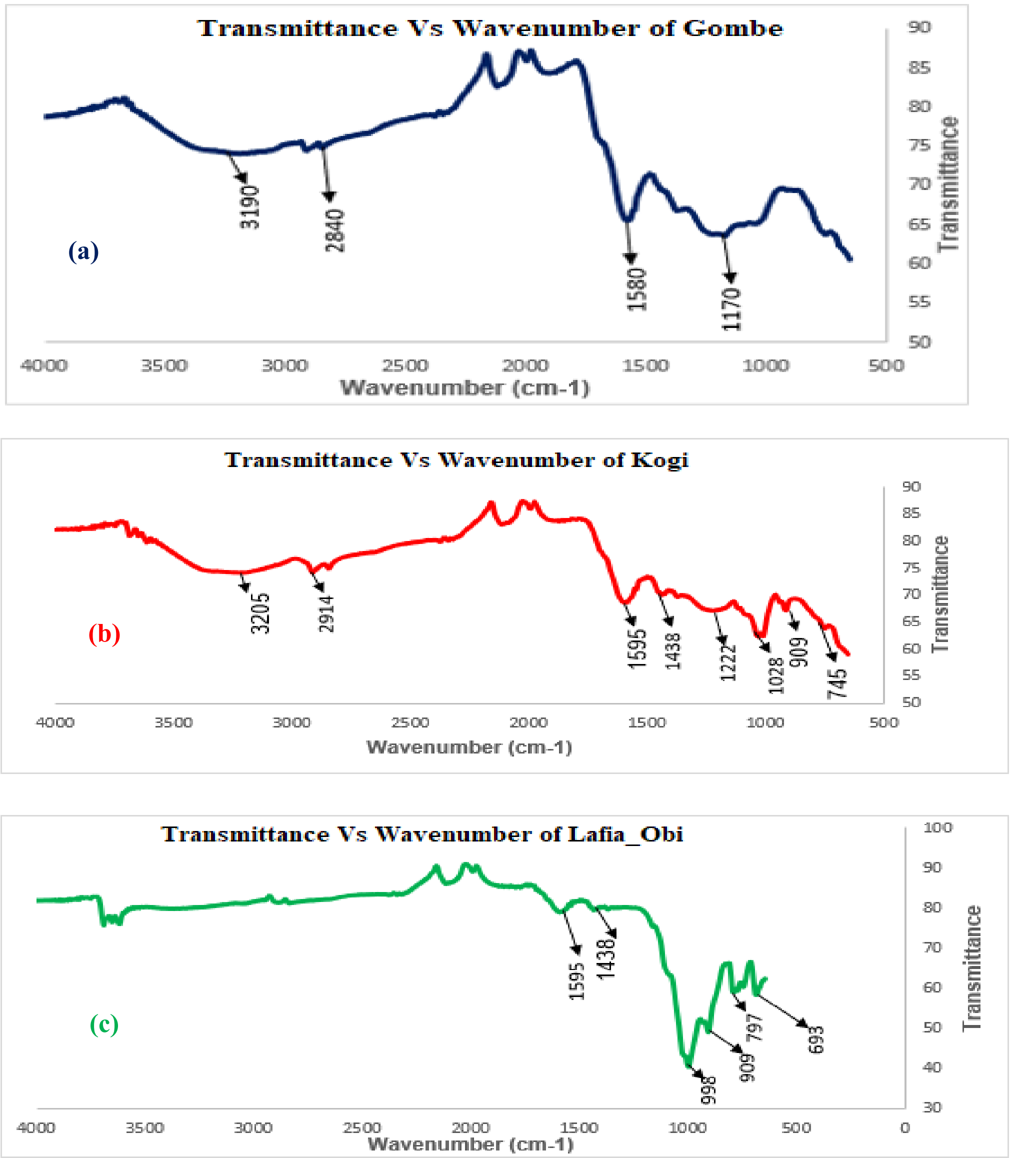

Figure 2: FTIR Results – Gombe (a), Kogi (b), and Lafia-Obi (c)

3.3 Thermogravimetric Analysis (TGA)

Figures 3 and 4 show the TGA/DTA profiles of the analysed samples. The Gombe coal sample shows a minor weight loss from 77 - 297 °C, probably from moisture evaporation. A substantial weight loss occurs (297 - 440 °C), likely due to the breakdown of volatile organic compounds, representing the main loss phase. Between 440 °C and 900 °C there is a gradual reduction in weight, which is probably due to the decomposition of the residual organic matter (Figure 4a). With regard to the Kogi coal, a minor loss takes place between 80

°C and 220 °C, this being probably the result of moisture evaporation; there is a considerable loss between 220 °C and 550 °C, likely caused by the decomposition of volatile organic compounds, and then a steady decline from 550 °C to 900 °C as a result of the breakdown of the remaining organic matter (Figure 4b). Interestingly, the Lafia-obi coal sample shows a small loss in weight between 57 °C and 250 °C due to moisture evaporation. A greater loss occurs between 250 °C and 450 °C, this being likely due to the decomposition of volatile organic compounds, with a gradual decrease from 450 °C to 900 °C caused by the breakdown of the remaining organic moieties (Figure 4c).

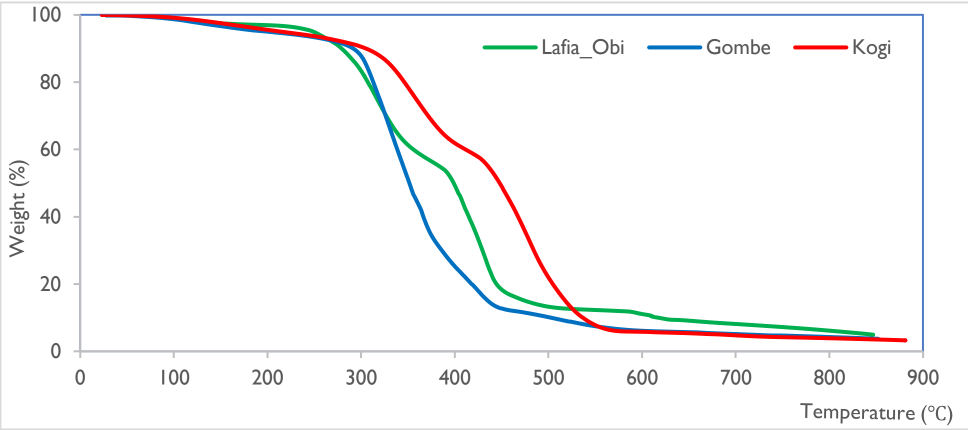

Figure 3: TGA profiles of analysed samples

3.4 X-ray Diffraction (XRD)

Certain minerals in coal can greatly influence its quality and whether it is suitable for use as coking coal. XRD analysis showed that the coal contains quartz, graphite, orthoclase, goethite, anatase, and microcline, as shown in Figure 5. Ideal coking coal should have high carbon content and very little inert minerals like quartz, feldspars, and iron oxides. Some minerals, such as graphite, can be helpful if they are present in the right form and amount. However, their effect depends on factors like how they are spread through the coal and the coking conditions, including how the coal is blended. Kogi coal is moderately suitable for coking due to its high graphite content, but this is offset by quartz and orthoclase, which contribute to ash, and by goethite, which reduces coking efficiency. Lafia-Obi coal also contains graphite. Quartz and microcline, which is less reactive than orthoclase, make it slightly better. Gombe coal also contains graphite, but the presence of quartz, orthoclase, and anatase makes the coal less desirable for coke production. The XRD results for Gombe, Kogi, and Lafia-Obi coals are shown in Figures 4, 5, and 6, respectively.

4. Coal Utilisation

Coal's rank and type are key determinants of its suitability for processes such as gasification, liquefaction, combustion and coking. The production of iron and steel, cement, electricity, and liquid fuels are among the industrial applications of coal.

4.1 Carbonisation (Coking)

Nigerian coal, in the form of coke, may be utilised in the Ajaokuta blast furnace for iron and steel making (Jauro and Chukwu, 2011). Coking coals are generally preferred to have a high carbon content (>75% ideal, >65% acceptable). In this regards, Lafia-Obi coal is the best among the three samples (70.63%), while Kogi and Gombe coal have 69.51% and 68.37%. Thus, all three samples have acceptable carbon contents. The three samples all have good nitrogen contents but low hydrogen. Kogi coal has the least oxygen content (4.30%), while Lafia-Obi coal has a high oxygen content (7%), and Gombe has 5%. Sulphur content is determined by each country's environmental emission laws but generally falls within 0.5-1.2%. Kogi coal has a low sulphur value of 0.23%, making it best; Lafia-Obi coal has 0.72%; and Gombe has the highest of the three samples (0.83%).

Based on the proximate analysis of the three samples, Lafia-Obi coal has the lowest moisture content at 2.96%. Gombe and Kogi coal have very high moisture contents of 9.09% and 11.97%, respectively, and thus require drying to reduce their moisture contents. Kogi and Gombe coal have low ash contents, while Lafia-Obi has a high ash content (13.41%) and requires ash reduction by washing or blending to improve its suitability.

Although Kogi coal has the highest volatile matter among the three samples, the volatile matter content of all three samples falls within the required range for coking. Lafia-Obi coal has a high fixed carbon value (56.40%), while Gombe coal has 54.87% and Kogi coal has the lowest fixed carbon (52.40%). Thus, Lafia-Obi coal is suitable for coking but would require considerable washing before use due to its high ash and sulphur contents (Fatoye and Gideon, 2013).

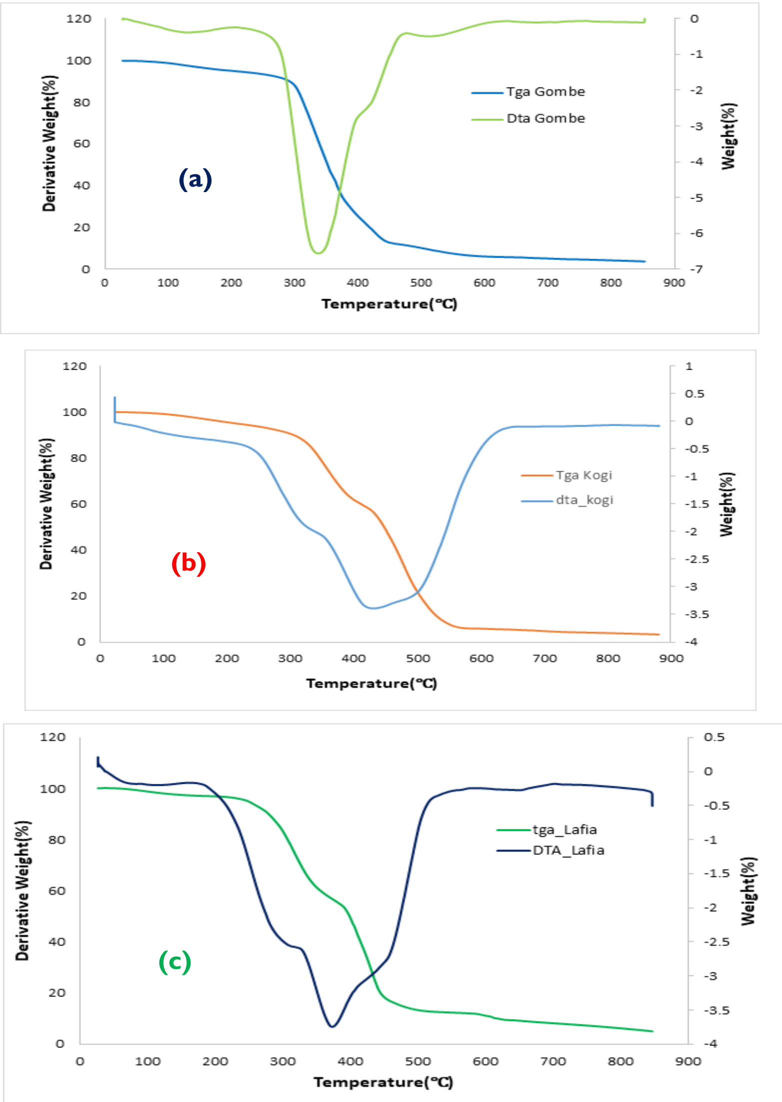

Figure 4: TGA/DTA profiles- Gombe (a), Kogi (b), and Lafia-Obi (c)

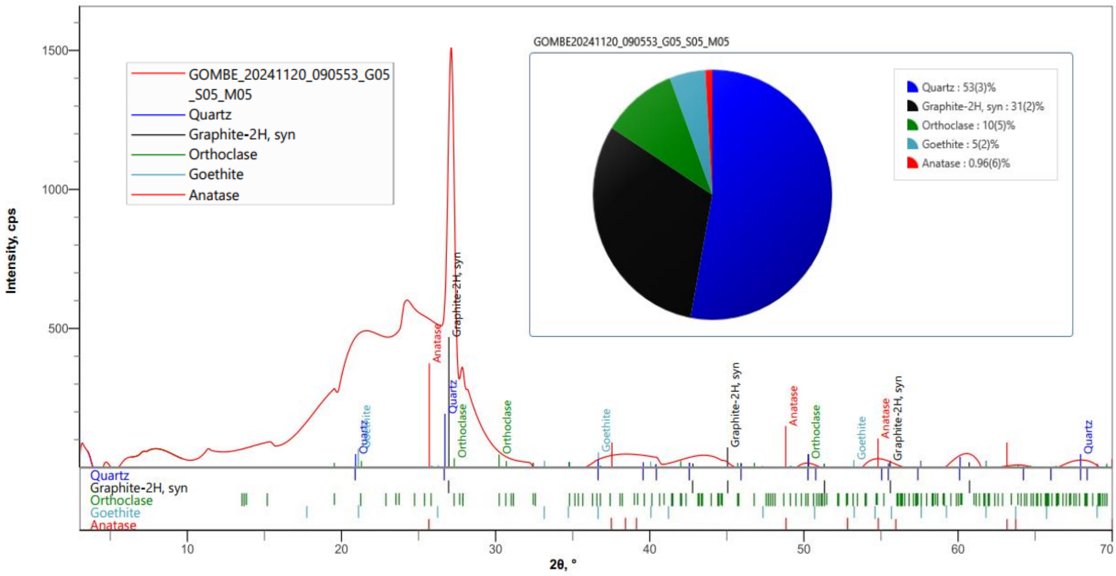

Figure 5: XRD result (Gombe coal)

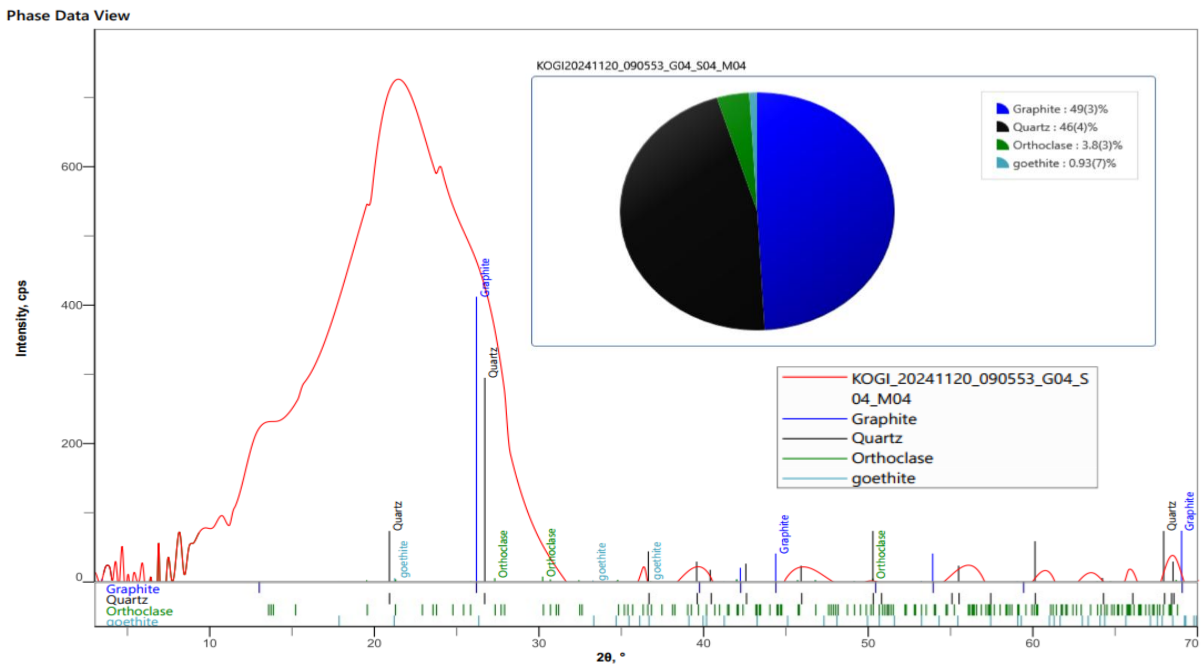

Figure 6: XRD result (Kogi coal)

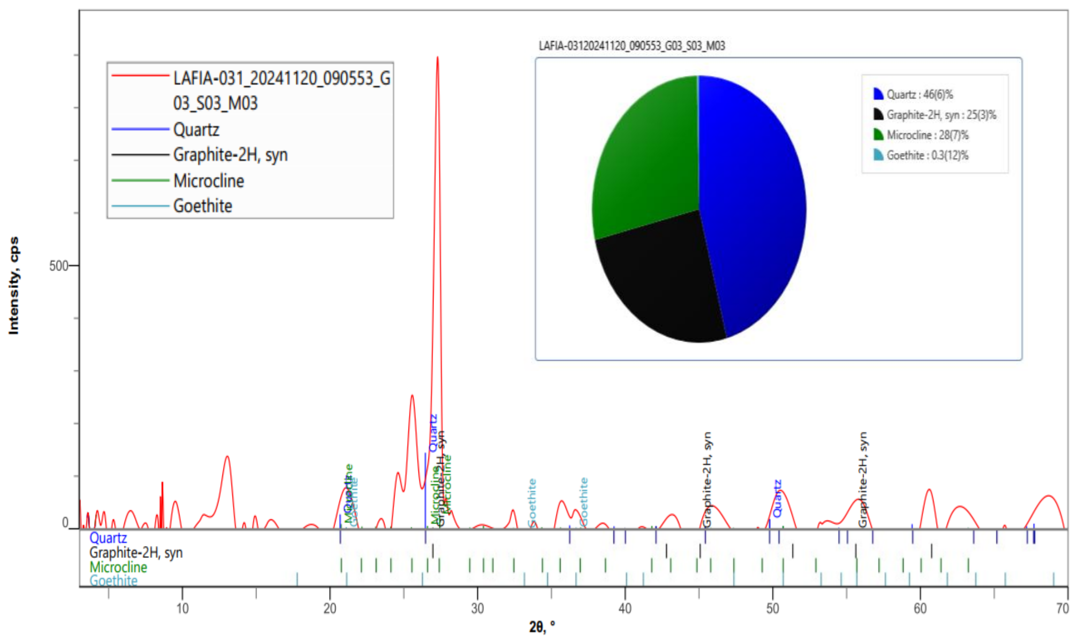

Figure 7: XRD result (Lafia-Obi coal)

4.2 Co-combustion

The energy sector worldwide is confronted with a major problem, namely the need to provide energy at a low cost without damaging the environment. One practical and efficient approach to reducing harmful emissions is to burn coal together with biomass, for example rice husk, sawdust, straw, or corn cob. This technique is one of the most effective methods of using biomass and provides a cheap, sustainable and renewable source of energy which helps to reduce the net emissions of CO_2, SOx, and NOx (Sahu *et al.* 2014; Yin *et al.* 2025). Due to the inherent moisture content in biomass, which reduces its heating value, it must be dried prior to co-firing (Verma *et al.* 2017).

Zhuikov *et al.* (2025) studied the ignition and combustion of coals of different ranks together with biomass. The findings indicated that when biomass was added to the coal (in amounts ranging from 10 to 230 wt.%) there was a reduction in both NOx and SOx emissions. The coal samples which have been analysed can be used together with the large amounts of biomass available in Nigeria to allow clean combustion of coal for the purpose of generating electricity. This will supplement the electricity produced by hydropower and gas power plants and thus support sustainable domestic and industrial use.

5. Conclusion

Coking coal is essential for the production of coke and can be used in the blast furnace of the Ajaokuta Steel Company to make iron and steel, thus helping to advance Nigeria's socio-economic development. Although some coals have coking qualities, others do not, and some types might harm the coke ovens. The data obtained in this study will assist in investigating the possible applications of the coals from the Benue Trough, either as blends for coking or for use in electricity generation through clean-coal co-combustion. The research indicates that the Kogi and Lafia Obi coals are promising as high-quality blends for coke production. On the other hand, Gombe coal can be employed in combustion, gasification, or liquefaction processes. Further research will involve the analysis of additional coal samples which have a variety of petrographic and rheological properties.

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