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Original Research

A Characterization Study of Raw Maiganga, Gombe Coal

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Abstract: The characteristics of individual coal deposits define its suitable applications, there is a need for a study on the detailed characterization of large coal deposits of Maiganga, Gombe coal, Nigeria. This work used the state of art analytical equipment to investigate the physicochemical properties, microstructural, elemental composition, mineralogy, functional groups, and thermal properties of the Maiganga coal. The proximate and ultimate analyses results depict that it is combustible with minimal impact on the environment and the calorific value of the coal (5179.80 kcal/kg) falls within the grade for energy recovery. The surface morphology revealed rough images that displayed the agglomerate network structure of the amorphous forms of coal, the coal contains heavy metals in form of oxides with combined major elements and trace metals. The phases found are quartz low (5.6%), cerussite (54%), lime (4.9%), and amesite (35.5%) with the crystalline size of 5.35 nm moreover, the functional group result showed different aliphatic –CH bonds exhibited by sub-bituminous coal. Thermal analysis revealed a temperature of >848.2 °C is required to decompose the Maiganga coal to obtain an efficient and high energy recovery and the ignition temperature at 285 °C, maximum weight loss temperature of 310 °C, and burnout temperature of 426 °C. This study identified the Maiganga coal as Low-Rank Coal (LRC), Sub-bituminous coal and is best suited for fertilizer, chemicals, cement, and electrical power production. Other possible applications are in catalysis, glass and ceramics production, fine chemicals, and nanomaterials.

Keywords: Cerrusite; Characterization; Energy; Properties; Maiganga coal; Temperature.

Introduction

Coal is an organic/sedimentary rock having more than 100 different minerals identified, its formation, properties, and ranking is influenced by factors such as pressure, constituents, geological evolution process, temperature and changes occurring during the coalification process, and mineralization [1-3]. Coal is commercially used as solid fuel [3], in the production of metallurgical coke grade used in iron production [4] and as the main ingredient in steel making. Other uses are Synthetic Natural Gas (SNG), fertilizer, cement production in electric-powered arc kilns that requires about 200 kg of coal to produce 1000 kg of cement [5].

In Nigeria, there is abundant coal of commercial quantities in Abia, Adamawa, Anambra, Bauchi, Benue, Cross-River, Delta, Ebonyi, Edo, Gombe, Imo, Kogi, Nasarawa, and Plateau States where their collective proven reserve is reported to be about 639 Mt, and inferred reserves of 2.75 Gt [6,7]. The Maiganga coal deposit Gombe, is found within the Gombe sandstone [8], the coalfield falls within the N-S trending Gongola basin of the northern Benue Trough, northeastern Nigeria [9]. There is a need for detailed characterization on the Maiganga coal since sufficient information can help the policymakers in deciding the coal suitable applications and the consequent diversification of the country's economy. Previously, Chukwu et al. [4] accessed the potentials of three Nigerian coals; Garin Maiganga, Lafia-Obi and Onyeama by proximate and X-Ray Fluorescence. In another study, the proximate and ultimate analyses, calorific value, acidity, pH value and alkalinity of Maiganga coal were revealed [10]. The comparative study of Enugu, Okaba and Maiganga coals by analytical methods including X-ray Fluorescence spectroscopy, thermosgravimetric analysis, proximate and ultimate analyses was conducted [11]. The physicochemical and thermogravimetric analysis of three discovered Nigerian coals; Afuze, Garin Maiganga and Shankodi-Jangwa were reported [1]. Akinyemi et al. [6] examined some selected Nigerian coals including Lafia-Obi, Imiegba, Garin Maiganga and Okaba coal using Fourier transform infrared ray spectroscopy, proximate and ultimate analyses, organic petrography, and thermogravimetric analysis. There is no single study that reported a detailed characterization of the Maiganga coal.

Coal combustion poses a potential threat of gigantic consequences to man and the environment therefore, the study of its properties which depends on various parameters to counter its devastative effects and properly utilize its full potential for the betterment of man and the environment must be carried out. The objective of this study is to undertake the detailed characteristics and analysis of Maiganga, Gombe coal through the ultimate, proximate, and calorific analyses. The coal is examined by various techniques, including Scanning Electron Microscopy (SEM), Energy Dispersive X-Ray Fluorescence (EDXRF), X-Ray Diffraction (XRD), Fourier Transform Infrared Spectroscopy (FTIR), and Thermogravimetric (TG) Analysis.

Materials and Methods

The coal sample is enquired at the mining site of Maiganga (Kobuwa area), Gombe State, Nigeria. The sample was crushed with a hammer to achieve particle size reduction afterward, the crushed samples were grounded with pestle and mortar then subsequently sieved using the 250 µm (mesh size – 60) size. The coal was analyzed by ultimate analysis and was deduced based on ASTM standard D3176-15 (LECO CHN analyser) and the proximate analysis was examined based on ASTM Standard D7582-12 [12]. Coal calorific value was determined using a bomb calorimeter (Model: IKA C2000) in accordance with the previous study [13]. The morphological and microstructural characterization of the coal samples were done by Scanning Electron Microscope (SEM) analysis. The tests were performed on the JEOLJSM IT 300 LV (Germany) SEM analysis. The coal sample is prepared according to Adedosu et al. [7] technique and the elemental analysis is carried out with Energy Dispersive X-ray Fluorescence Spectrophotometer (EDXRF) Analytical system (Model-XR300.50KV). The X-Ray Diffraction (XRD) analysis of Maiganga coal sample was carried out on the Rigaku XRD, with Cu (K-alpha) as a source of X-rays and the radiations generated at a tube voltage of 40Kv and tube current of 25 mA. PANalytical XPert' HighScore software version was used in quantitative mineralogical analysis and Originpro 2018 version was used to plot the XRD diffraction patterns. The FTIR imaging was carried out using Perkin Elmer RX for recording the spectra in the range of 3800-400 cm^{-1}. The thermal decomposition behavior of the coals was investigated by thermogravimetric analysis using the Perkin Elmer TG analyzer (Model: TGA 4000).

Results and Discussion

Proximate Analysis

The results of the proximate analysis of the Maiganga coal are shown in Table 1.

Table 1: Results of proximate Analyses of the Maiganga coal samples.

Fuel property	%
Moisture content	5.80
Ash content	8.00
Volatile matter	43.91
Fixed carbon	42.16

Moisture content is a significant parameter of coal since all coals are mined wet. The moisture content decreases with maturity and ranking of coal due to the decrease of porosity [14], the moisture content of below 10% for coal sample is within the acceptable limits for electric power generation [5]. It is found that ash content ranging from 5-40% is required for optimum utility coal therefore, Maiganga coal is containing low amount of ash content (8%). Some advantages of high Volatile Matter (VM) include an increase in flame length and easier coal ignition however, too high VM is associated to rapid and wasteful combustion of coal moreover, the utility coal range is within the range of 20-35% [13]. The VM value obtained for Maiganga coals fall out of the utility range. Fixed Carbon (FC) is the content of a coal sample that is remaining after VM is burnt out signifying carbon in its free state uncombined with other elements the FC of 42.16 is stated to be within the coke making range [10].

Ultimate Analysis

Ultimate analysis is dependent on quantitative analysis of various major elements present in the coal. The composition of carbon, hydrogen, nitrogen, sulphur and oxygen in the coal samples are shown in Table 2.

Table 2: Ultimate Analysis of Maiganga coal sample.

Element	Composition (%)
Carbon	69.486
Hydrogen	5.22249
Oxygen	10.5693
Nitrogen	1.2218
Sulphur	0.1340

Carbon and hydrogen are the major combustible constituents of coal, and both are high in the coal samples. The result revealed high proportions of the elements; carbon (69.486 %) and hydrogen (5.22249 %), these values fall within the characteristic of Low-Rank Coal (LRC) [15]. In a previous study, the Odagbo coal sample is reported to have high carbon (62.18%) and hydrogen (5.87%) contents therefore, it was classed as LRC [16]. Oxygen content in the samples is 10.5693%, the high content of oxygen is characteristic of LRC and high oxygen content eases coal to burn to ignite [15]. Also, the carbon content ranged 68-83% is classed as subbituminous [9], while high contents of C and O indicate carbonaceous materials with properties like coal [17]. The Nitrogen content

(1.2218%) falls within the range of subbituminous coal. The lower sulphur contents (0.134) depict that the Maiganga coal is suitable in a number of applications such as smokeless fuel production, heating of residential buildings, firing kiln for cement production, raising steam for power generation, and in foundry coke production and liquefaction to produce synthetic crude oil and tar, the similar finding is reported [18]. Calorific value defines the ability of the coal in heat generation and retention capacity and calorific value required for generating electricity of the range 2700 - 9500 Kcal/Kg [13], therefore, the Maiganga coal fall within the calorific values range required (5179.80 kcal/kg). Based on the proximate and ultimate analysis and calorific value, Maiganga coal could be identified as LRC, subbituminous coal and is best suited for fertilizer, chemicals, cement and electrical power production, other reported similar findings [18,19].

Morphology Analysis

The morphology appearance of the coal sample is shown by SEM analysis in Figure 1. The surface morphology revealed a rough image at various magnification (50 and 200 µm).

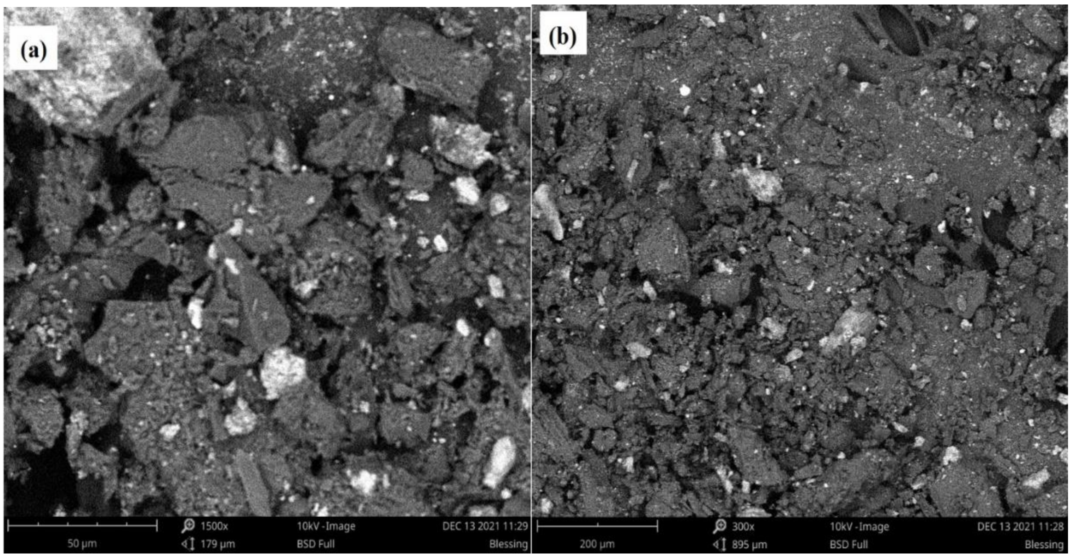

Figure 1: Surface morphology of Maiganga coal at different magnification of (a) 50 µm and (b) 200 µm.

The coal sample is anomalous in the shape of tablets, batting, platelets, and globules, further displaying the agglomerate network structure of the amorphous forms of coal in agreement to another study [3]. The shapes of dispersed particles observed are rough, spherical, and crystallite. White-colored grain is ascribed to quartz and many mineral phases while the coarse particles are ascribed to the presence of kaolinite, Fe and/or Ti [17].

Elemental Analysis

The knowledge of elemental composition is significant in coal applications, proper coal evaluation, maximum use of reserves, energy conservation, and environmental considerations. The composition of the inorganic portion often dictates the potentials of coal for any specific utilization process. The elemental composition is presented in Figure 2. For geochemical studies, both the major and minor elements are important and are found in coal samples [7], the mining and utilization of Maiganga coal can impact the environment through the Potentially Hazardous Traces Element (PHTEs). Based on the Energy Dispersive X-ray Fluorescence (EDXRF) Spectrophotometer, the Maiganga coal contains heavy metals in form of compounds or oxides with major elements;

SiO_2, Al_2O_3, CaO, Fe_2O_3, SnO, MgO while the minor elements are ZnO, Ga_2O_3, P_2O_5, SO_3, TiO_2, Rb2O, CuO, V2O5, BaO, Y_2O_3, PbO, Bi_2O_3, Ag_2O, WO_3, K_2O, As_2O_3, GeO_2, Br, I, Cl, Cr, Mn. This study agrees with the literature that the major species in coal include SiO_2, Al_2O_3, Fe_2O_3 [3]. The level of coalification is depicted by the presence of metals, and it is related to the salt, clay, or the porphyrin constituents in the coal structure furthermore, the composition of both minerals and metallic elements in the coal sample may be utilized in catalysis, glass and ceramics production, fine chemicals, and nanomaterials [5].

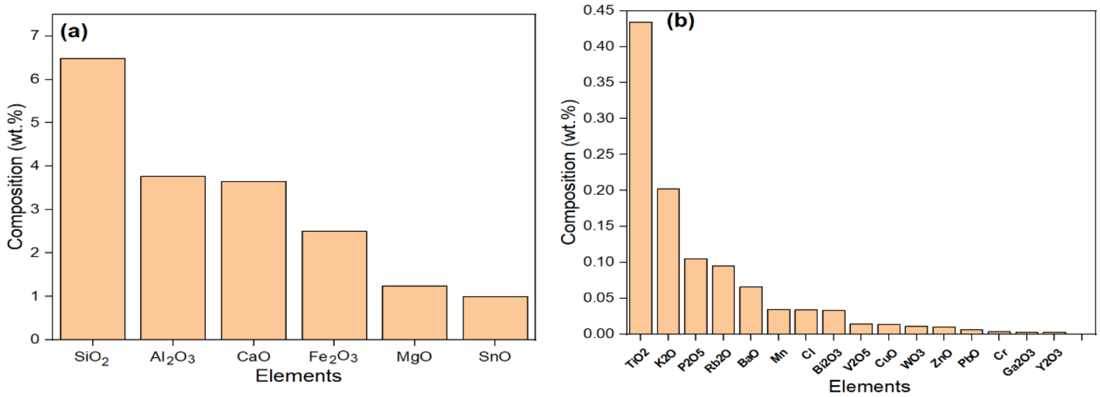

Figure 2: Elemental composition (a) Major and (b) Minor elements.

Mineralogical Analysis

There are many peaks of the phases shown in Figure 3, example, quartz low (SiO_2), cerussite ($PbCO_3$), lime (CaO), and amesite ($Mg_2Al_2SiO_5(OH)_4$ have the corresponding diffraction angles of 26.6°, 25°, 32.02°, and 36.6°, respectively.

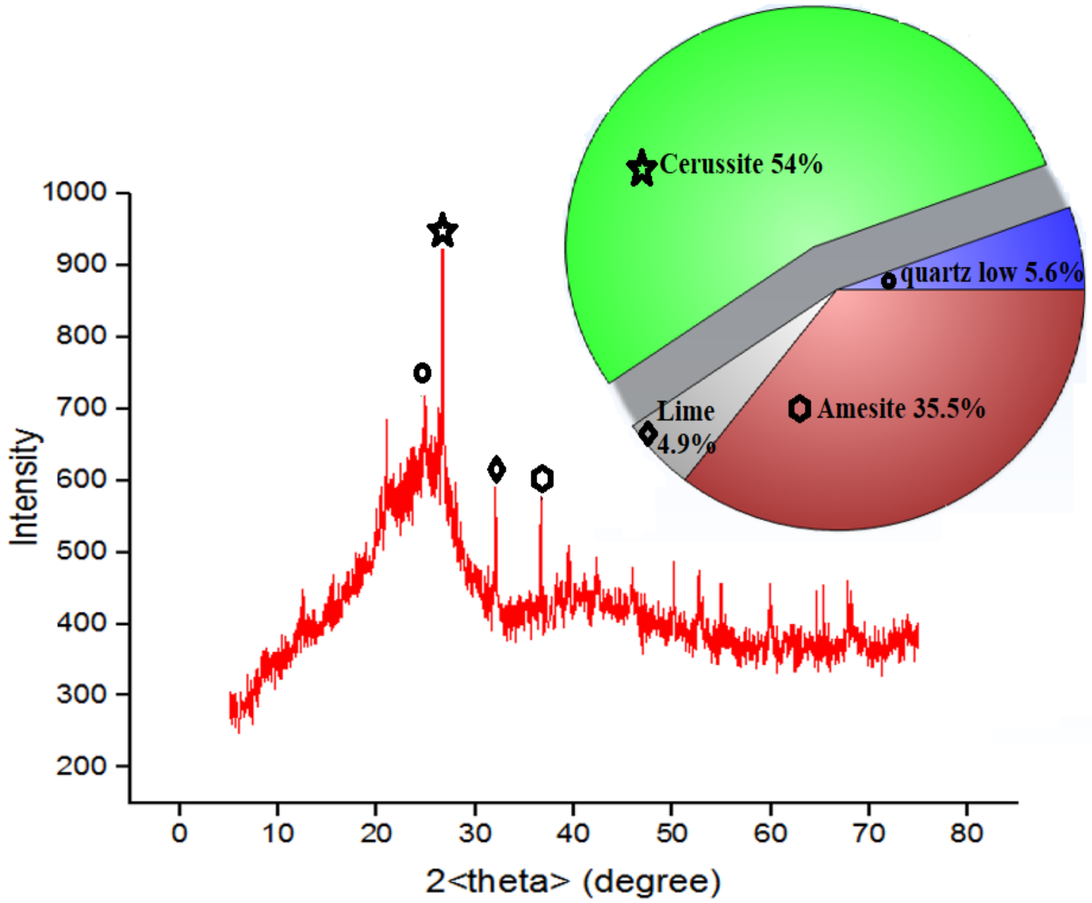

Figure 3: XRD diffraction of Maiganga coal.

The coal sample showed an amorphous carbon characteristic since the high background intensity indicates a certain proportion of highly disordered materials. The broad peaks appeared at the range of 26° to 32° which are stacks of aromatic molecules displayed by the diffraction of X-rays, similar findings can be found elsewhere [20]. The chemistry of coal depicts that the organic macromolecules are composed of a condensed aromatic nucleus and functional groups of non-crystal state materials [21]. Mostly, coal samples are amorphous materials [15]. This is indicated in the broadness of peaks, the coal pattern showed an amorphous halo centered at 2θ = 23O, which is the reflection of the plane (002) and a common feature of noncrystalline structures [22], corresponding to the microcrystals in the polycondensed aromatic ring and signifying to an amorphous carbon [23]. Furthermore, the crystalline size of the coal sample is deduced as 5.35 nm. The rietveld refinement was used to provide a semi-quantitative evaluation of the mineral phases in the form of percent relative abundance and cerussite (54%) is quantified as the major phase according to the XRD result. Among the lead oxide minerals, cerussite is found to be the most widespread mineral and an important source of lead metal [24]. Previous literature reported the presence of similar phases in coal samples example, Parvadeh Iranian low to medium volatile bituminous coals comprised of quartz, cerussite, and other phases [25]. Furthermore, about 35.5 % amesite is quantified in the raw coal as reported in a similar study [26], a small amount of amesite was detected on the XRD pattern of the Shenhua coal, an important China's steam coals, while in WJZ coal mine Guizhou, China the main minerals in the coal samples are quartz, kaolinite, and amesite [27]. The Lime phase is 4.9% as detected from the Maiganga coal sample, mostly, the lime phase is found in the XRD pattern of ash content of coal samples. To that effect, Huang et al. [28] reported the diffraction peaks of coals from Xinjiang, China as majorly kaolinite, quartz, and dolomite while the phases in ash were mullite and quartz which are converted from kaolinite and quartz, lime and calcite from dolomite.

Functional Groups Analysis

The quantity of different functional groups on the FTIR spectra in the 3800–1000 cm^{-1} band of the raw coal is presented in Figure 4.

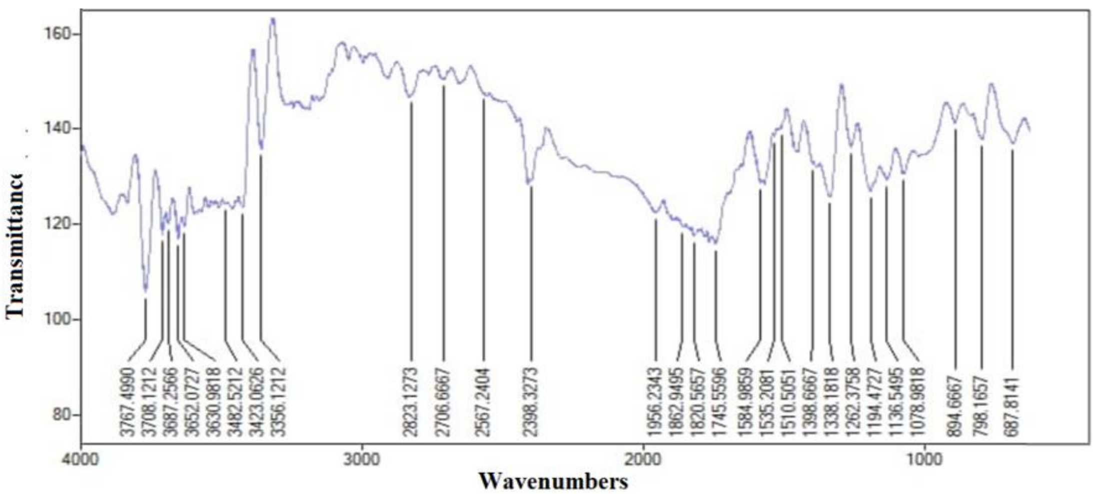

Figure 4: Functional groups on the FTIR spectra in the 3800–1000 cm^{-1} band of the raw coal.

The peak position on the spectra illustrates the presence of a certain functional group with the form of vibration it exhibits. Table 3 shows the functional groups in 3800–1000 cm^{-1} peak positions and its vibration forms.

Table 3: Functional groups in 3800–1000 cm^{-1} and its vibration form.

Peak position (cm^{-1})	Functional groups	Vibration form	Reference
3800– 3200	—OH and—NH	Stretching vibrations	[29,30]
3483	H_2O	Rota-vibrational bands	[6]
3600	O—H groups	Stretching vibrations	[29,30]
2398	C=N=O	Stretching vibrations	[6]
1770–1720	Aliphatic anhydride C=O	Stretching	[29]
1715–1690	COOH	Stretching	[29]
1690–1660	Quinone C= O	Stretching	[29]
1605–1595	C=O	Stretching	[6,29]
1510	C=C	Aromatic stretching	[6]
1480–1465	$—CH_2$	Antisymmetric deformation	[29]
1460–1435	$—CH_3$	Antisymmetric deformation	[29]
1410-1310	O—H groups	Stretching vibrations	[29]
1385–1370	$—CH_3$	Symmetrical bending	[29]
1338–1260	Ar—O—C	Stretching	
1250– 1000	Si— O	Bending vibration	[31]
1160–1120	C— O— C	Stretching	[29]
900–700	Aromatic —CH	out of plane structure.	[31,32]
690	C—S		[33]

The organic compounds having oxygen functional groups found in coal include phenols, alcohols, and carboxylic acid also, the –OH groups in raw coal could also be associated with either clay minerals such as kaoline, quartz, illite, montmorillonite, halloysite containing absorbed/interlayer water/structural –OH groups or other minerals containing water of crystallization such as gypsum, rozenite, mirabilite, etc [30,32,33]. The peak at 3423 cm^{-1} is due to the rota-vibrational bands of water vapor depicting the inherent water residual moisture in the coal, present in low-rank coals is the peaks observed at 1500 cm^{-1} [6], cerussite and quartz are observed at 1385 and 1160 cm^{-1} [34]. Furthermore, subbituminous coal samples have large absorptivities for different aliphatic –CH bonds [31]. From this study, very strong absorption was observed for different aliphatic –CH indicating that the Maiganga coal is ranked as subbituminous coal.

Thermal Analysis

The combustion behaviors of Maiganga coal through the Thermal decomposition (TG) and the Derivative Mass Loss (DTG) are presented in Figure 5a and b where the data were plotted against temperature to determine the thermal decomposition characteristic by pyrolysis for TG namely the Residual Mass (RM, %), Mass Loss (ML, %), and DTG namely Temperature Profile Characteristics (TPC); ignition temperature (T_{it}), maximum peak decomposition temperature (T_{max}), and burnout or offset temperature (T_{ot}). Steep TG plots for the burning profiles implied higher thermal degradation and ML can be seen for a downward Z-shaped curve in Fig. 5a depicting a typical carbonaceous material like the findings from TG plots of Akunza, Ome and Shiga coals of Nigeria reported previously [5]. The ML of 90.4% and RM of 9.6 can be observed, the result is signifying the thermochemical reaction is associated with low-ranked coals where the high number of reactive species are found in subbituminous coals [1]. The plot indicates a general thermal degradation from about 30-848.2 ^oC which was found to ascribed to the degradation of maceral (components of coal consisting of inertinite, vitrinite, and liptinite groups) or organic components of the coal while the degree of degradation largely depends on the maceral composition, rank, and physicochemical properties of coal [5]. Meanwhile, this finding indicates that a temperature of >848.2 °C is required to decompose the Maiganga coal to obtain an efficient and high-energy recovery. There is sharp mass loss at temperature 200 °C down 400 °C. Initially, a mass loss is observed at about 100 °C due to water loss in accordance with the previous study [35].

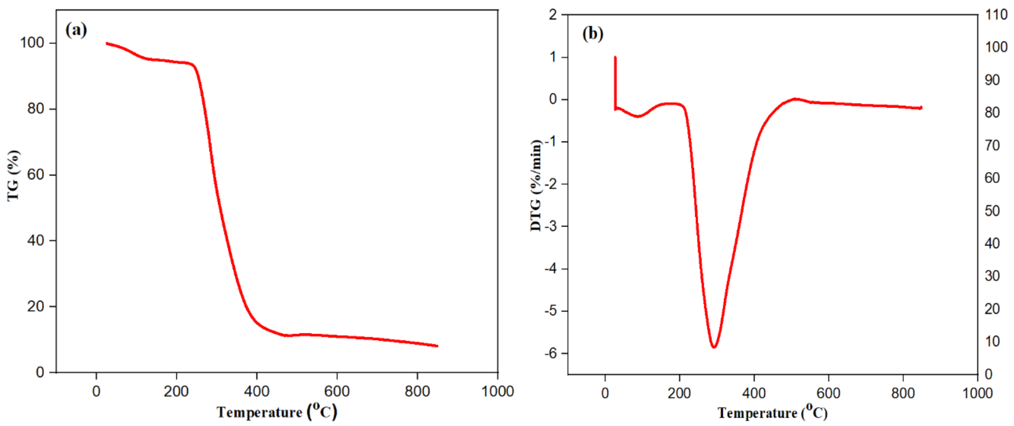

Figure 5: Plots for (a) TG combustion profile and (b) DTG combustion profile of Maiganga coal.

The reactivity of coal is deduced from the DTG plots which shows the three stages in the combustion process; the loss of low molecular weight volatile compounds and moisture content (drying) at 30-200 °C, loss of volatilization matter (devolatilization) at 200-500 °C which resulted to the production of condensable and non-condensable products and residual carbon (coke formation) at 500-848.2 °C, a similar finding has been reported in the literature [6]. The TPC result showed the ease of reactivity and ignition Tit, at 285 °C, the most significant temperature in weight loss T_{max}, at 310 °C, and the burnout temperature T_{ot}, 426 °C.

Conclusion

This study investigated the physicochemical, morphology, elemental composition, functional groups mineralogical, and thermal properties of the Maiganga coal. The coal sample has an appreciable amount of clay minerals or other minerals containing water of crystallization with characteristics associated with low-ranked coals and sub-bituminous that are best suited for fertilizer, chemicals, cement, and electrical power production.

Disclosure Statement

The author(s) did not report any potential conflict of interest.

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