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# Compositional, Structural, Mineralogical and Thermal Characterisation of Duduguru Coal from Benue Trough Nigeria for Potential Energy Recovery and Utilization

*Bemgba B. Nyakuma[1]*, Nasirudeen M. Baba[2], Aliyu Jauro [1,3], Segun A. Akinyemi[4], Mohammed S. Isyaka[1], John V. Anyam[1], Olagoke A. Oladokun[5]*

[1] *Department of Chemical Sciences, North-Eastern University, P. M. B. 0198, Gombe, Gombe State, Nigeria*
[2] *Department of Chemistry, Federal University of Lafia,P. M. B. 146, Lafia, Nasarawa State, Nigeria*
[3] *Department of Chemistry, Abubakar Tafawa Balewa University, P. M. B. 0248, Bauchi, Bauchi State, Nigeria*
[4] *Department of Geology, Ekiti State University,P. M. B. 5363, Ado-Ekiti, Ekiti State, Nigeria.*
[5] *Department of Chemical Engineering, Covenant University,P. M. B. 1023, Canaan Land Ota, Ogun State, Nigeria*

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**Abstract**

In this study, the compositional, structural, mineralogical and thermal characterisation of the newly discovered Duduguru (DDG) coal from Nasarawa State was conducted to examine its fuel and energy utilisation potentials. The compositional examination involved elemental, proximate, and calorific analyses, whereas microstructure/morphology and mineralogy were determined by scanning electron microscopy (SEM) and energy dispersive X-ray (EDX), respectively. The thermal examination involved heating the pulverised DDG coal from 25-900 °C using air (flowrate ϕ = 20 mL/min) to examine its combustion characteristics. Results revealed DDG contains high carbon (>60 wt.%) and hydrogen (>5 wt.%), fixed carbon (>52 wt.%) and higher heating value (>28 MJ/kg) but relatively low nitrogen (< 1.5 wt.%) and sulphur (<1 wt.%) contents. TGA revealed that DDG experienced significant thermal degradation, resulting in high weight loss (~83%) and low residual mass (~17%). Weight loss was ascribed to the degradation of macerals in DDG. The TG plot indicated onset, midpoint, and offset temperatures of 335.54°C, 538.72°C, and 708°C, respectively. The DTG plot revealed thermal degradation occurred in two major phases: stage I (25-200°C) and stage II (200-900°C), which was ascribed to drying/low-temperature degradation and macerals degradation, respectively. Overall, the findings demonstrate that the newly discovered DDG coal is suitable for energy recovery and utilisation in future power plants. Future studies could investigate the kinetic and thermodynamic properties of DDG coal often required in reactor design and optimisation for energy generation.

***Keywords:*** *Duduguru; Coal; Combustion; Power generation; Thermogravimetric analysis.*

## 1. Introduction

The International Energy Agency (IEA) estimates that coal-fired electricity accounts for ~38-40% of the global energy mix, i.e. about 228.29 EJ or 10,042 TWh [1]. Due to its abundance, cost-effectiveness, and geographic distribution [2], coal is considered an important fuel/feedstock for electric power generation in many regions of the globe [3]. Hence, coal-fired electricity generation could help to address the perennial energy crises afflicting developing countries like Nigeria [4]. Moreover, the discovery of novel and significant coal deposits in various Nigerian sedimentary basins presents timely and important opportunities for coal-fired electricity [5]. However, the lack of comprehensive data on the fuel characteristics and energy recovery potentials of Nigerian coals has long hampered the development of coal-fired power generation in the country [6-7].

Previous studies on Nigerian coals, such as Akande [8], investigated the petrographic composition and ranks of selected Upper Cretaceous and Tertiary coals of southern Nigeria. Obaje [9] examined the petrography, microfossils, and paleoenvironments of Cretaceous coals from the Middle Benue Trough (MBT) of Nigeria. In a separate study, Obaje [10] examined the petrographic composition and depositional environments of Cretaceous coals and coal measures from the MBT region of Nigeria. Ehinola [11] investigated the geology and geochemistry of Lafia-Obi coal from the Benue Trough, Nigeria. Studies on the source-rock and liquid hydrocarbon potentials of mid-Cretaceous coals and coal measures in the MBT have also been reported in the literature [12]. Ogala [13] examined the petrography, mineralogy, and geochemistry of selected lignite coals from the Ogwashi–Asaba Formation in Nigeria. Ryemshak and Jauro [14] reported on the rheological properties of selected Nigerian coals from the Upper Benue Trough region of Nigeria. More recently, Akinyemi [15] investigated the organic facies, elemental geochemistry, and paleodepositional settings of some Cretaceous coals from Nigeria's Benue Trough Basin.

The review of the literature shows that previous research studies on Nigerian coals have been largely limited to geological aspects such as petrography, geochemistry, rheology, mineralogy, paleoenvironments, and depositional environments. However, there is limited data on the fuel properties and energy characteristics of such coals, which is required for the design, development, operation, and optimisation of process technologies for coal conversion and application. Chukwu [16] performed a comprehensive characterisation of selected coals across Nigeria to examine their power generation potential. Akinyemi [17] employed petrologic, physicochemical, and thermochemical techniques to explore the fuel and energy characteristics of selected Cretaceous coals from the Benue Trough Basin, Nigeria. Nyakuma [18] examined the mineralogical, physiochemical, and thermo-kinetic properties of selected coals from the Benue Trough and Anambra Basins, Nigeria.

Despite the progress recorded over the years, these studies are limited to well-known coals, which presents opportunities for the examination of the newly discovered samples. In this study, the compositional, structural, mineralogical and thermal characterisation of the newly discovered Duduguru (DDG) coal from Nasarawa State was conducted to examine its potential for energy recovery and utilisation.

## 2. Experimental methodology

### 2.1. Sample materials

The Duduguru (DDG) coal sample examined in this study is a newly discovered coal from Duduguru, Obi Local Government Area of Nasarawa State in Nigeria. The DDG coal sample was acquired from the coal deposit in the locality through a mixture of grab/ incremental sampling to obtain representative samples. About 50 kg of the DDG sample was sampled, subsequently tagged, and bagged for transportation to the Hydrogen and Fuel Laboratory, Universiti Teknologi Malaysia Johor, for various analyses.

### 2.2. Experimental methods

#### *2.2.1. Physicochemical characterisation*

The compositional characterisation of the DDG sample involved analysing its elemental, proximate, and calorific properties. Ultimate analysis was conducted to compute the carbon, hydrogen, nitrogen, and sulphur (CHNS) contents. CHNS analysis was performed via the vario MACRO cube Organic Elemental Analyzer (Germany), whereas oxygen content was computed by difference from CHNS components. Proximate properties comprising the moisture, ash and volatile matter were determined using the NeyTech Vulcan muffle furnace (Model: Model D-130, USA) based on ASTM D3173, D3174, and D3175 standards, respectively. The calorific property (higher heating value (HHV)) of DDG was determined using the Leco AC350 bomb calorimeter.

### 2.2.2. Microstructural & morphological characterisation

The microstructure and morphology of DDG were determined by scanning electron microscopy (SEM). Before each analysis, the sample was sputter coated with a thin film of gold (Au) using the Quorum Q150R S device (UK). The sample was degassed and sequentially scanned using the JEOL JSM-IT300 SEM analyser (Japan) to determine its microstructure and morphological properties. Details of the SEM procedure are described in our previous publications [19-20].

### 2.2.3. Mineralogical characterisation

The mineral characterisation of DDG coal was determined using an energy-dispersive X-ray (EDX) spectrophotometer. The EDX analysis was carried out to obtain further insights into the composition of chemical elements undetected by the elemental (ultimate analysis) procedures. For each test, the DDG SEM micrograph was scanned using the point ID and mapping feature of the AZTEC EDX software (Oxford Instruments, UK), which computationally elucidated the composition of mineral elements in weight per cent (wt.%).

### 2.2.4. Thermal characterisation

The thermal properties of DDG were examined using thermal gravimetric analysis (TGA). For each test, approximately 12.786 mg of sample was heated under non-isothermal conditions from 25 °C to 900 °C under air atmosphere (flowrate, $\phi$ = 20 mL/min) conditions at 50 °C/min using the Shimadzu TG-50 thermal analyser (Japan). The objective was to examine the unique degradation behaviour and thermal profile characteristics of DDG coal under rapid heating rates typically observed during pulverised coal combustion (PCC). The detailed procedure for sample preparation and analysis was adopted from our previous study [21].

## 3. Results and discussion

### 3.1. Physicochemical properties

The physicochemical characterisation of DDG coal was performed to elucidate its elemental, proximate, and calorific fuel properties for potential energy recovery and utilisation for power generation applications. Table 1 presents the compositional properties of the DDG coal sample examined in this study. It is important to state the elemental, proximate, and calorific analyses are presented on dry ash-free basis, dry, and as-received basis, respectively. The as-received moisture content of DDG coal was 6.48 wt.%.

Table 1. Physicochemical and calorific properties of DDG coal.

| Characterization | DDG property | Symbol (unit) | DDG coal |
|---|---|---|---|
| Ultimate analysis | Carbon | C (wt.%) | 64.11 |
| | Hydrogen | H (wt.%) | 5.90 |
| | Nitrogen | N (wt.%) | 1.39 |
| | Sulphur | S (wt.%) | 0.67 |
| | Oxygen | O* (wt.%) | 27.92 |
| Proximate analysis | Moisture | $M^{\dagger}$ (wt.%) | 6.48 |
| | Volatile matter | VM (wt.%) | 35.33 |
| | Ash | A (wt.%) | 11.87 |
| | Fixed Carbon | FC (wt.%) | 52.81 |
| Calorific analysis | High heating value | HHV (MJ/kg) | 28.41 |

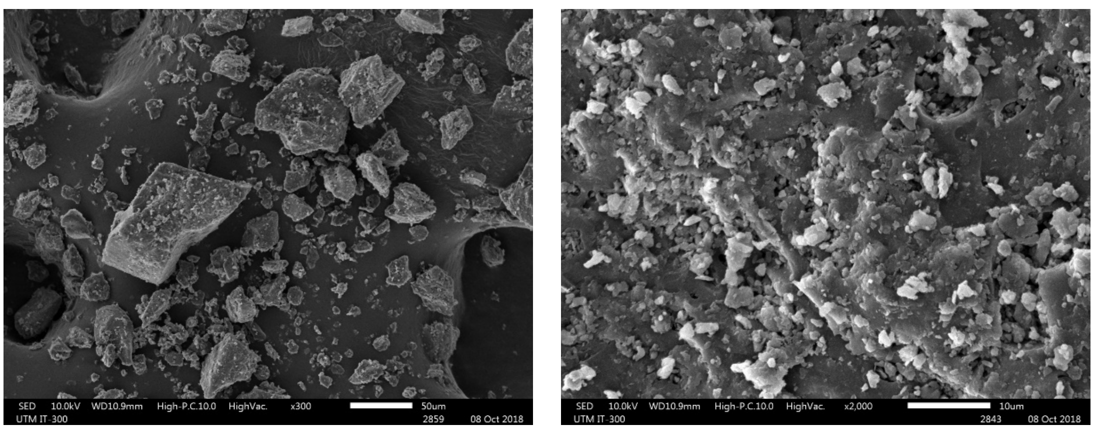
** Computed by difference; † As received moisture content.*

The CHNS analysis reveals that DDG coal contains high carbon (> 60 wt.%) and hydrogen (> 5 wt.%) but relatively lower contents of nitrogen (*N*) and sulphur (*S*) (< 2 wt.%). These findings indicate that DDG has a high composition of combustible elements that are required for energy recovery. In contrast, the relatively low *N* and *S* content suggests that relatively low greenhouse gas emissions (GHG), such as NOx and SOx, could be emitted during the PCC of the sample. However, further analysis of DDG coal using TGA and mass spectroscopy (MS) may be required to shed more light on its GHG emissions profile.

Proximate analysis revealed that DDG contains high fixed carbon (> 50 wt.%), volatile matter (> 30 wt.%), and ash (> 10 wt.%). The high FC carbon content may account for the high energy content and high combustion efficiency during PCC. Additionally, the high FC content points to good coking potential for DDG [22-23], which could have potential applications in the steel and metallurgical industry. Nonetheless, high FC, along with high ash (>10%), could hamper the rates of ignition, combustion, and waste generation potentials of DDG during PCC [24-25]. The impact of fuel properties was examined through thermal analysis, as presented in Section 3.4. Calorific analysis revealed that DDG has an HHV of 28.41 MJ/kg, which is somewhat higher than other Nigerian coals such as Owukpa (26.51-26.67 MJ/kg) [16,26], Obomkpa (19.66 MJ/kg), Ihioma (19.40 MJ/kg) [27], Garin Maiganga (22.95 MJ/kg), Shankodi-Jangwa (27.34 MJ/kg) [28], among others.

### 3.2. Microstructural and morphological properties

The microstructural and morphological properties of DDG were examined through scanning electron microscopy (SEM). Figure 1 presents the SEM micrographs of DDG coal examined at magnifications of (a)×300 and (b) ×2000. The micrographs show the presence of white-coloured, round-to-spherical-shaped, and exfoliated coal particles. The white-coloured grains denote the presence of quartz, whereas the coarse-shaped particles denote the presence of kaolinite and other clay minerals [29-30].




a. b.

Figure 1. SEM micrographs of DDG coal.

### 3.3. Bulk elemental properties

Table 2 presents the elemental composition of DDG coal determined by EDX analysis. The results indicate that DDG contains a combination of metals and non-metal elements in its composition. The selection of non-metals consists of carbon, oxygen, and sulphur, whereas the metals include silicon, aluminium, iron, calcium, titanium, and magnesium. As observed, carbon has the highest weight and atomic composition of elements, ranging from 69.23-76.93%, followed by oxygen (20.02-24.00%), and lastly silicon (2.36-4.97%). The presence of carbon indicates the presence of organic materials or matter, which is transformed into Coal over the years and, as such, is critical to its chemical properties [31]. The presence of silicon, aluminium, and oxygen denotes the presence of aluminosilicate minerals, which consist of quartz, feldspars and clay minerals in the coal structure [32]. It is widely reported that the inorganic content and ash produced during coal combustion are facilitated by silicate minerals [33-34]. It impacts the environmental and functional elements of coal consumption by influencing the properties of ash and the thought process surrounding ash disposal [35].

Lastly, the presence of iron and sulphur indicates that DDG contains pyrite ($FeS_2$). Pyrite is regarded as the most prevalent and abundant sulfide component that plays a crucial role in the handling and utilisation of coal [36-37]. Pyrite is the primary cause of acid mine drainage and the primary generator of $SO_2$ (a precursor to acid rain) during coal combustion [36]. Although it occurs in small proportions, it could undergo stepwise decomposition, forming ferrous sulfide (FeS) [37-38] and eventually organic sulfur compounds and $H_2S$ [39]. However, there is empirical evidence suggesting that pyrite plays a catalytic role in the liquefaction and gasification of coal [36].

Table 2. EDX elemental composition of DDG coal.

| Elements | Symbol | Weight % | Atomic % | Standard label |
|---|---|---|---|---|
| Carbon | C | 69.23 | 76.93 | C Vit |
| Oxygen | O | 24.00 | 20.02 | $SiO_2$ |
| Silicon | Si | 4.97 | 2.36 | $SiO^2$ |
| Aluminium | Al | 0.52 | 0.26 | $Al_2O_3$ |
| Iron | Fe | 0.41 | 0.10 | Fe |
| Calcium | Ca | 0.33 | 0.11 | Wollastonite |
| Sulphur | S | 0.24 | 0.10 | $FeS_2$ |
| Titanium | Ti | 0.16 | 0.04 | Ti |
| Magnesium | Mg | 0.15 | 0.08 | MgO |

### 3.4. Thermal properties

The thermal conversion and utilisation of Coal for energy applications require a comprehensive analysis of its degradation behaviour and thermal profile characteristics [40-41]. In this study, the combustion of pulverised DDG coal was examined through thermal gravimetric analysis (TGA). Figure 2 presents the TG/DTG plots for the combustion of pulverised DDG coal under non-isothermal conditions from 25 °C to 900 °C. As observed, the plot displays the typically downward-sloping curves indicating the weight loss of a material during TGA. DDG coal experienced significant thermal degradation, resulting in 83.47% weight loss and 16.53% mass of residuals. The thermal profile characteristics indicate that the onset of DDG coal degradation began at 335.54°C, whereas the midpoint temperature occurred at 538.72°C, and lastly, the endpoint temperature was observed at 708°C. Based on the data, it could be reasonably surmised that DDG coal degradation chiefly occurred between 336 °C and 708°C. These findings indicate that the process, parameters, and technologies for conversion of DDG could be tailored within the range of 335-710°C to ensure effective energy recovery and power generation. The DDG coal degradation could also be ascribed to the decomposition of organic macerals, namely inertinite, liptinite, and vitrinite, between 400°C and 800°C [42-43]. The mass loss has also been ascribed to the condensation of aromatics and mineral matter degradation arising from high-temperature secondary degassing reactions [44].

The DTG plots reveal two endothermic peaks in the temperature ranges from 25°C to 200°C and 300°C to 900°C. This observation indicates that DDG coal experienced a two-stage degradation. The weight loss during the first stage could be ascribed to the loss of moisture (drying) and the degradation of low molecular weight compounds [43], which results in a maximum peak temperature of 100.26°C. The second stage could be mostly attributed to the breakdown of macerals, specifically vitrinite, which is the most prevalent maceral fraction after liptinite and inertinite, in decreasing order of abundance [42-44]. The maximum peak degradation in the second stage was observed at 432.93°C, which not only falls within the range (< 600°C) for the degradation of vitrinite [45] but also confirms its significance in DDG coal degradation.

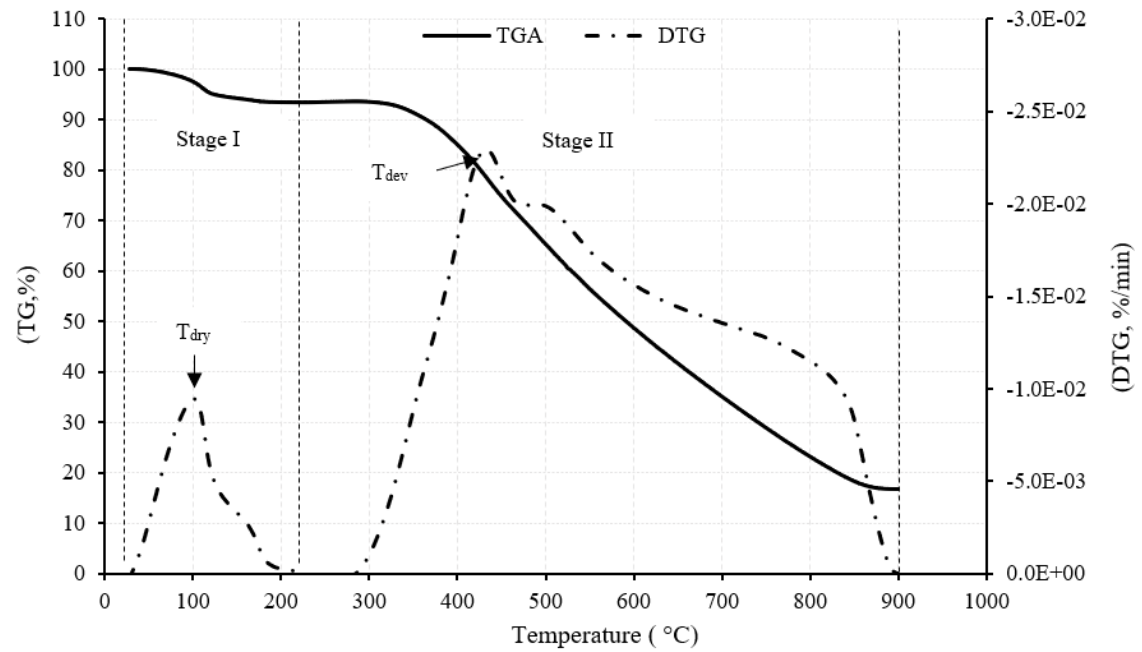



Figure 2. TG/DTG plots for DDG coal.

## 4. Conclusions

The study examined the compositional, microstructural, mineralogical, and thermal properties of Duduguru (DDG), which is a newly discovered coal from Nasarawa State (Nigeria). The results showed that DDG contains high levels of carbon, hydrogen, fixed carbon, and higher heating value but low levels of moisture, nitrogen, and sulphur, which indicates it is a suitable fuel for combustion for energy recovery and utilisation. The SEM analysis revealed that the pulverised DDG coal contains heterogeneous, varied-shaped particles that indicate the presence of quartz and clay minerals, which were confirmed by the bulk chemical analysis. Thermal analysis revealed DDG experienced significant thermal degradation evident in the high weight loss (>83.47%) and low mass of residuals (17.16%), which was ascribed to the conversion of coal macerals and release of volatile matter. Overall, the study showed that DDG contains the requisite physicochemical, microstructural, and thermal properties required for pulverised coal combustion. As such, this newly discovered coal is well suited for energy recovery and utilisation in coal-fired power generation. Future studies can build on the findings to examine its thermo-kinetic and thermodynamic properties for reactor design and electricity generation.

### References

[1] IEA. Coal powered electricity. Coal-Fired Electricity 2021 [cited 2023 26th May]; Energy Report]. Available from: https://tinyurl.com/34s56pfk.

[2] Speight JG. The Chemistry and Technology of Coal. Third Edition ed. 2012, USA: Taylor & Francis Publishers.

[3] Miller BG. Coal energy systems. 2005: Academic Press.

[4] Ohimain EI. Can Nigeria generate 30% of her electricity from Coal. International J. Energ. Power Eng. 2014; 3(1): pp. 28-37.

[5] Nyakuma BB, Jauro A, Akinyemi SA, Faizal HM, Nasirudeen MB, Fuad MAHM, and Oladokun O. Physicochemical, mineralogy, and thermo-kinetic characterisation of newly discovered Nigerian coals under pyrolysis and combustion conditions. Int. J. Coal Sci Techn. 2021; 8(4): pp. 697-716.

[6] Nyakuma BB. Physicochemical, geomineralogical, and evolved gas analyses of newly discovered Nigerian lignite coals. Cok. Chem. 2019; 62: 394-401.

[7] Akinyemi SA, Nyakuma BB, Jauro A, Adebayo OF, OlaOlorun OA, Adegoke AK, Aturamu AO, Adetunji A, Gitari WM, Mudzielwana R. Mineralogy, physicochemical and oxidative thermal analyses of Cretaceous coals from the Benue Trough, Nigeria. Energ. Geosci. 2021; 2(2): 129-135.
[8] Akande SO, Hoffknecht A, Erdtmann BD. Rank and petrographic composition of selected Upper Cretaceous and Tertiary coals of southern Nigeria. Int. J. Coal Geol. 1992; 20(3-4): 209-224.
[9] Obaje NG. Coal petrography, microfossils, and paleoenvironments of Cretaceous coal measures in the Middle Benue Trough of Nigeria. Tubinger Mikropalaeotologische Mittellungen, 1994; 11: 74-89.
[10] Obaje N, Ligouis B, Abaa S. Petrographic composition and depositional environments of Cretaceous coals and coal measures in the Middle Benue Trough of Nigeria. Int. J. Coal Geol. 1994; 26(3-4): 233-260.
[11] Ehinola OA, Ekweozor C, Oros D, Simoneit B. Geology, geochemistry and biomarker evaluation of Lafia-Obi coal, Benue Trough, Nigeria. Fuel, 2002; 81(2): 219-233.
[12] Obaje N, Hamza H. Liquid hydrocarbon source-rock potential of mid-Cretaceous coals and coal measures in the Middle Benue Trough of Nigeria. Int. J. Earth Sci: Geolog. Rundsc. 2000; 89(1): 130.
[13] Ogala J, Siavalas G, Christanis K. Coal petrography, mineralogy and geochemistry of lignite samples from the Ogwashi–Asaba Formation, Nigeria. J. Afr. Earth Sci. 2012; 66: 35-45.
[14] Ryemshak SA, Jauro A. Proximate analysis, rheological properties and technological applications of some Nigerian coals. Int. J. Indust. Chem. 2013; 4: 1-7.
[15] Akinyemi SA, Adebayo OF, Madukwe HY, Kayode AT, Aturamu AO, OlaOlorun OA, Nyakuma BB, Jauro A, Gitari WM, Mudzielwana R. Elemental geochemistry and organic facies of selected Cretaceous coals from the Benue Trough Basin in Nigeria: Implication for paleodepositional environments. Marin. Petrol. Geo. 2022; 137: 105490.
[16] Chukwu M, Folayan C, Pam G, Obada D. Characterization of some Nigerian coals for power generation. J. Combust. 2016; Article ID 9728278.
[17] Akinyemi S, Adebayo O, Nyakuma B, Adegoke A, Aturamu O, OlaOlorun O, Adetunji A, Hower JC, Hood MM, Jauro A. Petrology, physicochemical and thermal analyses of selected cretaceous coals from the Benue Trough Basin in Nigeria. Int. J. Coal Sci. Tech. 2020; 7: 26-42.
[18] Nyakuma BB, Akinyemi SA, Wong SL, Oladokun O, Jauro A, Abdullah TAT. Physiochemical, Mineralogical, Thermal and Kinetic Characterisation of Selected Coals from the Benue Trough and Anambra Basin, Nigeria. Cok. Chem. 2021; 64(11): 496-507.
[19] Nyakuma BB, Jauro A, Oladokun O, Akinyemi SA, Nasirudeen MB, Bello AA, Alkali H, and Abdullah TAT. Fuel characteristics of Duduguru coal from Nasarawa State in Nigeria. Petroleum and Coal, 2019; 61(4): 682-689.
[20] Nyakuma BB, Jauro A, Akinyemi SA, Nasirudeen MB, Oladokun O, Bello AA, Ivase TJP, Abdullah TAT. Physicochemical Fuel Properties and Carbonization Kinetics of Duduguru Coal. Pet. Coal. 2020; 62(4): 1153-1162.
[21] Nyakuma BB. Combustion of Duduguru Coal: Physico-Chemical, Thermogravimetric, and Kinetic Studies. Cok. Chem. 2022; 65(11): pp. 521-530.
[22] Nyakuma BB, Oladokun O, Abdullah TAT, Ojoko EO, Abdullahi MG, El-Nafaty AS, and Ahmed AA. Carbonization and Coke Characteristics of Ogboligbo Coal. Cok. Chem. 2018; 61(11): 424-432.
[23] Das S, Sharma S, and Choudhury R. Non-coking coal to coke: use of biomass-based blending material. Energy, 2002; 27(4): 405-414.
[24] Bada S, Falcon R, and Falcon L. Characterization and co-firing potential of high ash coal with Bambusa balcooa. Fuel, 2015; 151: 130-138.
[25] Nyakuma BB, Oladokun O, Akinyemi SA, Ojoko EO, Jacob GA, Abdullah TAT, Alkali H, and Al-Shatri, AH. Comprehensive Evaluation of the Combustion Kinetic Characteristics of Owukpa Coal. Cok. Chem. 2019; 62(8): 371-378.
[26] Nyakuma BB, Ojoko EO, Oladokun O, Bello AA, Aboje AB, Ivase TJP, Al-Shatri AH, and Alkali H. Fuel characterisation and thermal degradation behaviour of Owukpa Coal. Pet. Coal, 2018; 60(6): 1142-1148.
[27] Nyakuma BB. Burning characteristics and fuel properties of Obomkpa, Ihioma, and Ogboligbo lignite coals from Nigeria. Pet. Coal, 2019; 61(2): 262-268.
[28] Nyakuma BB. Physicochemical Characterization and Thermal Analysis of newly discovered Nigerian coals. Bul. Chem. Comm. 2016; 48(4): 746-752.
[29] Garzanti E, Andò S, and Vezzoli G. Settling equivalence of detrital minerals and grain-size dependence of sediment composition. Earth Planet. Sci. Lett. 2008; 273(1-2): 138-151.

[30] Sengupta P, Saikia PC, and Borthakur PC. SEM-EDX characterisation of an iron-rich kaolinite clay. J. Scientif. Indust. Res. 2008; 67: 812-818.
[31] Sellaro R, Sarver E, and Baxter D. A standard characterisation methodology for respirable coal mine dust using SEM-EDX. Resources, 2015; 4(4): 939-957.
[32] Michalski JR, Kraft MD, Sharp TG, Williams LB, and Christensen PR. Emission spectroscopy of clay minerals and evidence for poorly crystalline aluminosilicates on Mars from Thermal Emission Spectrometer data. J. Geophys. Res.: Planets, 2006; 111(E3).
[33] Miller SF, and Schobert HH. Effect of the occurrence and composition of silicate and aluminosilicate compounds on ash formation in pilot-scale combustion of pulverised Coal and coal-water slurry fuels. Energy & Fuels, 1994; 8(6): 1197-1207.
[34] Niu Y, and Tan H. Ash-related issues during biomass combustion: Alkali-induced slagging, silicate melt-induced slagging (ash fusion), agglomeration, corrosion, ash utilisation, and related countermeasures. Prog. Energy Comb. Sci. 2016; 52: 1-61.
[35] Wang CA, Zhao L, Sun R, Hu Y, Tang G, Chen W, Du Y, Che D. Effects of silicon-aluminium additives on ash mineralogy, morphology, and transformation of sodium, calcium, and iron during oxy-fuel combustion of Zhundong high-alkali Coal. Int. J. Greenhouse Gas Contr. 2019; 91: 102832.
[36] Chen H, Li B, Zhang B. Decomposition of pyrite and the interaction of pyrite with coal organic matrix in pyrolysis and hydropyrolysis. Fuel, 2000; 79(13): 1627-1631.
[37] Zhao H, Bai Z, Guo Z, Kong L, Yuchi W, Li H, Bai J, Li W. In situ study of the decomposition of pyrite in Coal during hydropyrolysis. J. Analyt. Appl. Pyr. 2021; 154: 105024.
[38] Zhao H-L, Bai Z-Q, Yan J-C, Bai J, Li W. Transformations of pyrite in different associations during pyrolysis of Coal. Fuel Process. Tech. 2015; 131: 304-310.
[39] Furfari S, René C. Hydropyrolysis of a high-sulphur, high-calcite Italian Sulcis coal: 3. Pyrite behaviour. Fuel, 1983; 62(5): 615-619.
[40] Nyakuma BB. Determination of the combustion characteristics of Chikila coal through the Kissinger kinetics model. Chem. Chem. Tech. 2020; 14(3): 433-438.
[41] Nyakuma BB, Jauro A, Oladokun O, Abdullah TAT, Uthman H. Combustion kinetics of Shankodi-Jangwa coal. J. Phys. Sci. 2016; 27(3): 1-12.
[42] Landais P, Muller J-F, Michels R, Oudin J-L, and Zaugg P. Comparative behaviour of coal and maceral concentrates during artificial coalification. Fuel, 1989; 68(12): 1616-1619.
[43] Xie W, Stange R, Lucas J, Wall T, and Mahoney M. Coal macerals separation by reflux classification and thermo-swelling analysis based on the Computer Aided Thermal Analysis. Fuel, 2013; 103: 1023-1031.
[44] Zou C, Ma C, Zhao J, Shi R, and Li X. Characterization and non-isothermal kinetics of Shenmu bituminous coal devolatilisation by TG-MS. J. Analyt. Appl. Pyr. 2017; 127: 309-320.
[45] Mishra V, Sharma M, Chakravarty S, and Banerjee A. Changes in organic structure and mineral phases transformation of Coal during heat treatment on laboratory scale. Int. J. Coal Sci. Tech. 2016; 3: 418-428.

*To whom correspondence should be addressed: Dr. Bemgba B. Nyakuma, Department of Chemical Sciences, North-Eastern University, P. M. B. 0198, Gombe, Gombe State, Nigeria, E-mail: bbnyax1@gmail.com, bemgba.nyakuma@neu.edu.ng https://orcid.org/0000-0001-5388-7950*