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# FUEL CHARACTERISTICS OF DUDUGURU COAL FROM NASARAWA STATE IN NIGERIA

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**Abstract**

The discovery of vast deposits of various ranks of coal in Nigeria presents significant opportunities to address the nation's persistent energy crises. However, the lack of comprehensive data on the physico-chemical, calorific, microstructural, mineralogical, and thermal properties of Nigerian coals remains a significant challenge. Therefore, this paper seeks to investigate the fuel characteristics and energy recovery potential of a newly discovered coal from Duduguru in Obi Local Government Area of Nasarawa State, Nigeria. Results revealed that Duduguru (DDG) coal contains high carbon (59.6%), oxygen (32.9%), volatile matter (76.4%), fixed carbon (16.6%) and higher heating value (HHV = 26.6 MJ/kg), but low nitrogen (1.3%), sulphur (0.6%), moisture (6.5%), and ash (0.5%) content. Based on these properties, DDG is classified as a non-agglomerating, sub-bituminous, grade "A" coal with potentials for electricity generation, cement production, among others. The mineralogical analyses revealed quartz, kaolinite, and aluminosilicates are present in its microstructure. Thermal analysis revealed that DDG is more thermally reactive under flash combustion (FCO) based on its higher mass loss ($M_L$) and lower residual mass ($R_M$) compared to flash pyrolysis (FPY) conditions. The temperature profile characteristics of DDG under FCO were considerably lower than the FPY. In conclusion, the findings indicate that combustion is a more practical route for efficient energy recovery from DDG coal in the future.

***Keywords***: *Fuel characterization; Energy; Duduguru; Coal; Nasarawa; Nigeria.*

## 1. Introduction

The discovery of vast deposits of various ranks of coal in Nigeria presents significant opportunities to address the nation's persistent energy crises [1]. Despite Nigeria's position as Africa's largest economy and most populous nation, socioeconomic growth and sustainable development remain a significant challenge [2]. Many analysts have attributed the nation's energy crises to numerous socioeconomic, geopolitical, environmental, and technological challenges [3]. Most notably, the lack of comprehensive data on Nigerian coals has hampered progress in the area of power plant development, efficient energy recovery, and resource management [4-5]. Currently, the available data on Nigerian coals is mostly limited to their geological, petrographic, and seismologic properties [6-9]. However, these properties of coal are not crucial for energy recovery, resource management or the design and operation of coal-fired power plants.

Currently, coal accounts for 35 – 40% of global electricity production around the globe [10]. As a result, coal is considered a widely accessible and economically reliable source of cheap electricity for socioeconomic growth and sustainable development, particularly in developing countries with significant resources [11-12]. Numerous studies have reported that Nigeria has over 640 million proven tonnes of coal along with 2.75 billion tonnes of inferred reserves comprising 12% lignite, 49% subbituminous and 39% bituminous [4]. Furthermore, studies have reported that deposits of Nigerian coals are evenly distributed across the six geopolitical zones of Nigeria [13]. Therefore, the exploration, examination, and exploitation of coal for electricity production could potentially address the nation's energy crises, alleviate poverty, and spur long term socio-economic growth and sustainable development.

However, this is expedient on addressing the current challenges posed by poor power generation, transmission, distribution and maintenance. This will be particularly important in coal-fired power plants, which require considerable attention, particularly in the era of global calls for fossil fuel diversification. Furthermore, comprehensive data and knowledge on the fuel properties of various ranks of Nigerian coals will assist in the design, operation, and maintenance of future power plants in the country particularly in the agricultural, mining, and minerals development areas like Nasarawa State, which also has vast deposits of coal in the areas around Atito-Akpuneje, Shankodi-Jangwa and Lafia-Obi [14-16].

Therefore, the primary objective of this paper is to examine the fuel characteristics and energy recovery potential of a newly discovered coal from Duduguru, Obi Local Government Area of Nasarawa State in Nigeria. The paper presents the physicochemical, calorific, microstructural, mineralogical, and thermal properties of Duduguru (DDG) coal. To the best of the author's knowledge, this paper is the first comprehensive examination of the fuel proper-ties, classification, and potential applications of DDG coal from the Middle Benue Trough of Nigeria's sedimentary basin. The findings will provide comprehensive insights on the fuel properties and energy recovery potentials of DDG coal.

## 2. Materials and methods

### 2.1. Physicochemical analyses

The physicochemical analysis of the Duduguru (DDG) coal was carried out by ultimate, proximate, and bomb calorimetry methods. The ultimate analysis was carried out to determine the elemental carbon, hydrogen, nitrogen and sulphur (CHNS) composition of the sample using the CHNS analyser (Model: vario MACRO Cube, Germany). Proximate analysis was determined according to the ASTM standards D3173, D3174, and D3175 for moisture, ash and volatile matter contents, respectively. The calorific or higher heating value was determined using the Isoperibol bomb calorimeter (Model: Leco AC350, UK) based on the ASTM standard D240-17. All tests were carried out in duplicate to ensure the reliability and accuracy of the measurements.

### 2.2. Microstructure and mineralogy analyses

The microstructure (morphological) and mineralogical analyses of Duduguru coal were carried out through scanning electron microscopy (SEM) and energy dispersive x-ray (EDX) spectroscopy. For each test, the Quorum Q150R S apparatus was employed to sputter coat the DDG sample with gold. The sputter coated DDG sample was degassed and subsequently transferred to the SEM/EDX analyser for microstructure and mineralogical examination. The operational settings of the SEM/EDX analyser were set at voltage 20 kV, working distance 5 mm, and ×1000 magnification. On completion, the SEM image was examined using the proprietary AZTEC EDX software from Oxford Instruments (UK). The point ID and mapping feature were subsequently employed to deduce the composition of mineral elements in weight per cent (wt. %).

### 2.3. Thermal analysis

The thermal properties of Duduguru (DDG) coal were examined by thermogravimetric analysis (TGA) under oxidative and non-oxidative conditions to simulate flash combustion (FCO) and flash pyrolysis (FPY), respectively. For each test, approximately 11 mg of the sample was placed in an alumina crucible and heated under a non-isothermal heating programme from 30°C to 1000°C in a high precision thermogravimetric analyser (TGA Model: Shimadzu TG-50, Japan). For the flash combustion (FCO) and flash pyrolysis (FPY) processes, the TG analyser was flushed with air and ultra-pure nitrogen (purge gas flow rate 20 mL/min), respectively, to purge out the gases evolved during TGA. On completion, the raw data for the mass loss and derivative mass loss were retrieved and analysed to deduce the TG (%) and DTG (%/min) data, respectively. The TG-DTG data was subsequently plotted against temperature to examine the thermal degradation behaviour and characteristics temperature profiles of the sample.

### 2.4. Temperature profile analyses

The temperature profile characteristics (TPC) of Duduguru (DDG) coal were examined based on the tangent method described in the literature [17]. This is embedded in the data analysis feature of the Shimadzu Thermal analysis software (Version: Workstation TA-60WS). The TPCs deduced for the flash combustion (FCO), and flash pyrolysis (FPY) of DDG coal in this study include; the ignition ($T_{ons}$), midpoint ($T_{mid}$), maximum decomposition ($T_{max}$), and burnout ($T_{off}$) temperatures along with the mass loss ($M_L$, %) and residual mass ($R_M$, %). The detailed description of the temperature profile characteristics (TPC) was presented in our previous study [18].

## 3. Results and discussion

### 3.1. Physicochemical properties

Table 1 presents the fuel properties of Duduguru (DDG), reported in as-received (a.r.) basis and compared with other Nigerian coals from Garin Maiganga (GMG) and Shankodi-Jangwa (SKJ) [15].

Table 1. Fuel properties of Duduguru (DDG) coal

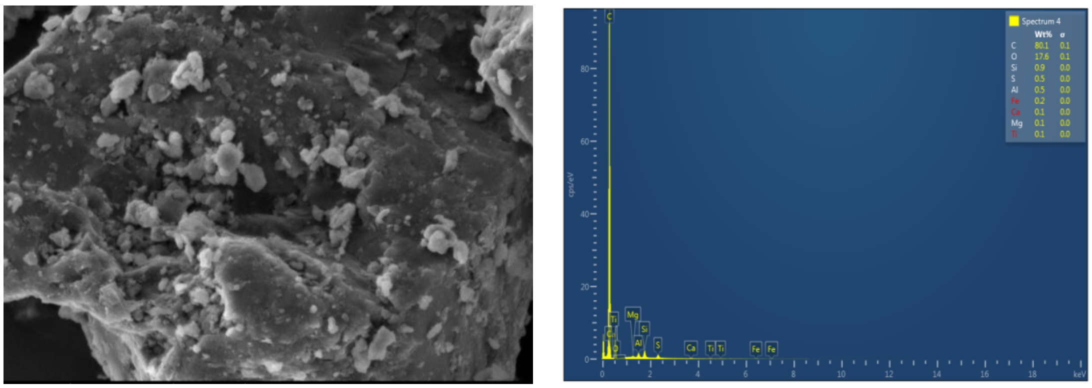
| Element/ Fuel Property | Symbol/Unit | Duduguru (DDG) (This study) | Garin-Maiganga (GMG) [15] | Shankodi-Jangwa (SKJ) [15] |
|---|---|---|---|---|
| Carbon | C (wt.%) | 59.64 | 61.96 | 71.46 |
| Hydrogen | H (wt.%) | 5.49 | 4.42 | 6.40 |
| Nitrogen | N (wt.%) | 1.30 | 1.07 | 1.37 |
| Sulphur | S (wt.%) | 0.62 | 0.39 | 2.03 |
| Oxygen | O (wt.%) | 32.95 | 32.16 | 18.76 |
| Moisture | M (wt.%) | 6.48 | 5.28 | 5.14 |
| Volatile matter | VM (wt.%) | 76.42 | 51.16 | 40.73 |
| Ash | A (wt.%) | 0.50 | 21.05 | 14.94 |
| Fixed carbon | FC (wt.%) | 16.60 | 22.52 | 39.18 |
| Higher heating value | HHV (MJ/kg) | 26.55 | 22.95 | 27.34 |

As observed, the DDG coal sample contains high contents of carbon (C > 55%), hydrogen (H > 5%), and oxygen (O > 30%) but low values of nitrogen (N) and sulphur (S) all below 5%. Furthermore, the sample contains low moisture (M), and ash (A) contents, which are in good agreement with GMG and SKJ reported in the literature [15]. However, the constituents of volatile matter (VM) and fixed carbon (FC) are significantly higher than reported for similarly ranked coals in literature.

The calorific analysis indicated that DDG coal has a higher heating value of 26.6 MJ/kg. In comparison, the HHV of DDG is somewhat similar to Owukpa (26.51 – 26.67 MJ/kg) [4, 19], but lower than Afuze (30.52 MJ/kg) [20], and Shankodi- Jangwa (27.34 MJ/kg) [21], which are other subbituminous Nigerian coals described in literature. Based on the ASTM D388-12 [22] standard for classification of coals based on HHV, the DDG coal can be classified as a non-agglomerating, sub-bituminous, grade A coal. This indicates that DDG could be potentially utilised for power generation, cement and other industrial applications [23].

### 3.2. Microstructure and mineralogy properties

The utilisation of coals for various applications, particularly pulverised combustion, requires in-depth knowledge on its mineral composition. This is crucial to the design, operation and maintenance of boilers as well as solid waste and evolved pollutant gas emissions in coal power plants. Therefore, this paper examines the microstructure and mineralogy of DDG coal. The SEM micrograph (magnification ×1000) for DDG is shown in Figure 1(a), whereas the EDX spectrum and chemical data reported are presented in Figure 1(b) and Table 2, respectively.



(a) (b)

Figure 1. SEM Micrograph (a) and EDX Spectra (b) for DDG

As observed in the SEM micrograph, the morphology and microstructure of DDG consist of a wide range of medium to large particles that are rough, spherical and crystallite in shape dispersed on its smooth layered surface. Typically, the presence of the white coloured, round, exfoliated or spherical shaped grains is ascribed to quartz [24-25]. This highlights the recycled nature and maturity of the accumulated sediment [25]. However, the coarse particles observed in the micrograph are ascribed to the presence of kaolinite [26]. Kaolin particles are characterised by rolled or rough edges with face to face arrangement. Similarly, the coarse fraction of DDG coal observed in the SEM micrograph may be due to the presence of metallic elements such as Ti and Fe, which typically bear various minerals such as pyrite [25].

The mineralogical composition of the coal sample was subsequently examined, as presented in Table 2, respectively. The characteristic peaks of the elements detected during the EDX analysis are presented in Figure 1(b).

Table 2. Mineral composition of DDG

| Mineral element | Symbol of element | Weight % (wt.%) | Atomic (%) |
|---|---|---|---|
| Carbon | C | 80.08 | 85.01 |
| Oxygen | O | 17.55 | 13.99 |
| Magnesium | Mg | 0.12 | 0.07 |
| Aluminum | Al | 0.49 | 0.23 |
| Silicon | Si | 0.87 | 0.39 |
| Sulphur | S | 0.53 | 0.21 |
| Calcium | Ca | 0.13 | 0.04 |
| Titanium | Ti | 0.07 | 0.02 |
| Iron | Fe | 0.15 | 0.03 |

The results indicate that the elements C, O, Mg, Al, Si, S, Ca, Ti, and Fe were detected in significant and trace quantities during the EDX analysis. The major elements (i.e. with composition > 0.5 wt.%) were; C, O, Si, S, and Al, whereas the minor elements detected were Mg, Ca, Ti, and Fe. The results show that C, Ti, Fe exist in elemental form in the structure of DDG, whereas as O, Mg, Al, Si, S, and Ca exist in combined form as mineral compounds. However, the elements Mg, Al, Si and Ca exist in the form of the oxides MgO, $Al_2O_3$, $SiO_2$ and $CaSiO_3$ (wollastonite), respectively.

The elements Al and Si indicate the presence of mixed carbonaceous, aluminosilicate and quartz minerals [27]. The mixed carbonaceous elements may be due to the presence of thin clay minerals or clay minerals with some carbon content, whereas the aluminosilicates indicate the presence of clay minerals and feldspars [28-29]. In addition, the quartz could be due to the presence of crystalline silica materials in the coal structure [30]. Lastly, the high contents of C and O indicate carbonaceous materials with properties similar to coal [27].

### 3.3. Thermal properties

The thermal properties of Duduguru (DDG) coal were examined by thermogravimetric analysis (TGA) under flash (heating rate, $\beta$ = 50°C/min) oxidative (combustion) and inert (pyrolysis) conditions. The TG, conversion and DTG plots for the thermal degradation of DDG coal are presented in Figures 2-4, respectively. As observed, the DDG coal sample experienced progressive mass loss under the flash combustion and pyrolysis conditions examined in this study. The TG plots showed that the increase in temperature from RT to 1000°C significantly decomposed the sample during TGA. This is ascribed to increase in thermal energy, which enhanced the thermal degradation of the macerals (organic) fraction in DDG. As a result, there was an increase in the conversion of the sample, as illustrated in Figure 3.

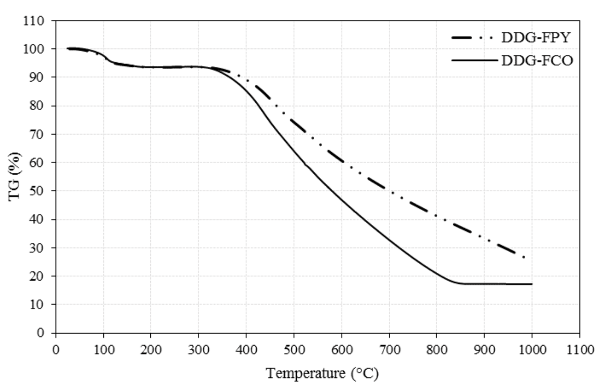


Figure 2. TG plots for flash combustion (FCO) and pyrolysis (FPY) of DDG

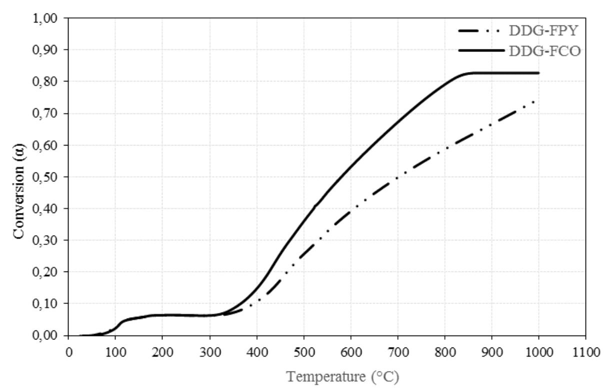


Figure 3. Conversion plots for flash combustion (FCO) and pyrolysis (FPY) of DDG

Therefore, it can be surmised that higher temperatures enhanced the conversion of the coal components due to the increase in the bond breaking reactions of the coal components during TGA. The findings indicate that DDG is thermally reactive and can be effectively degraded into coal products or for efficient thermal energy recovery, either under oxidative or non-oxidative thermal conditions as examined in this study.

Next, the degradation pathway for the thermal degradation of DDG coal was examined through DTG analysis, as presented in Figure 4. The DTG plots of thermally decomposing carbonaceous materials present valuable insights into the mechanism, reaction steps, and temperature profiles of the process [5].

As observed in Figure 4, the thermal decomposition of DDG generated two major endothermic peaks under oxidative (FCO) and inert (FPY) conditions. The first peaks were observed from 30°C to 250°C, which can be ascribed to drying or the loss of moisture. However, the second major peaks occurred in the range 250°C to 850°C for FCO whereas for the FPY process it was from 250°C to 980°C. The mass loss in these ranges could be ascribed to the loss of volatile matter or organic matter content of DDG through devolatilization. Overall, the findings indicate that temperature significantly influenced the thermal degradation of DDG irrespective of whether the reaction occurred under oxidative or inert conditions during TGA. The extent of the degradation of the sample was subsequently examined to determine the temperature profile characteristics (TPCs).

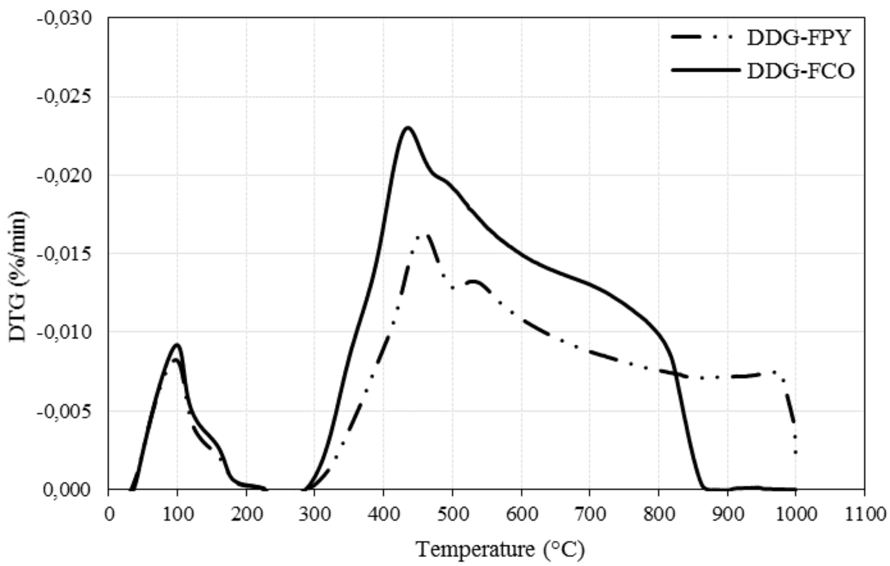



Figure 4. DTG plots for flash combustion (FCO) and pyrolysis (FPY) of DDG

### 3.4. Temperature profile characteristics

The temperature profile characteristics (TPC) of Duduguru (DDG) coal were examined to deduce the thermal degradation behaviour of the sample under flash oxidative (FCO, combustion) and inert (FPY, pyrolysis) conditions. The TPCs for DDG examined in this study include; ignition ($T_{ons}$), midpoint ($T_{mid}$), maximum decomposition ($T_{max}$), and burnout ($T_{off}$) temperatures along with mass loss ($M_L$, %) and residual mass ($R_M$, %), as presented in Table 3.

Table 3. TPC values for DDG under FCO and FPY conditions

| Process | Onset temp. ($T_{ons}$, °C) | Midpoint temp ($T_{mid}$, °C) | Burnout temp ($T_{off}$, °C) | Mass loss ($M_L$, %) | Residual mass ($R_M$, %) |
|---|---|---|---|---|---|
| FPY | 350.73 | 557.94 | 732.03 | 74.22 | 25.78 |
| FCO | 336.75 | 528.51 | 688.82 | 82.90 | 17.10 |

The results pyrolysis (FPY) of DDG occurred from 350.73°C to 732.03°C, whereas the flash combustion (FCO) process was between 336.75°C and 688.82°C. This indicates that the ignition and burnout of DDG during FCO occurred at lower temperatures compared to the FPY process. In addition, the midpoint ($T_{mid}$), and maximum decomposition ($T_{max}$) temperatures of FCO were lower than the FPY process. This resulting pattern is ascribed to the oxidative nature of the FCO process, which ensured the DDG coal experienced higher thermal energy and hence higher mass loss ($M_L$ = 83.0%) compared to FPY ($M_L$ = 74.2%). Besides, the observation may be due to the exothermic reactions arising from the oxidative nature of the FCO process. As a result, the coal components were more efficiently degraded during FCO, resulting in lower residual mass ($R_M$ ~ 17.1%) compared to the FPY process ($R_M$ ~ 25.8%). Therefore, it can be reasonably inferred that the FCO process is a more thermally reactive and resource efficient process compared to FPY.

## 4. Conclusion

This study examined the fuel characteristics and energy recovery potential of a newly discovered coal sample from Duduguru in Obi Local Government Area of Nasarawa State, Nigeria. Consequently, the elemental, proximate, calorific, microstructure, mineralogical, and thermal analyses of Duduguru (DDG) coal was examined. The proximate and ultimate analyses revealed that DDG has high carbon (C), volatile matter (VM) and fixed carbon (FC) contents. However, the sample showed low nitrogen (N), sulphur (S), moisture (M), and ash (A) contents. The calorific value showed that DDG has a higher heating value (HHV) of ~26.6 MJ/kg, indicating its potential for efficient energy recovery during thermal conversion. The microstructure and mineralogical analyses revealed medium to large particles with wide-ranging shapes typically ascribed to quartz, kaolinite and other aluminosilicate minerals. The thermal properties of DDG coal studied under flash combustion (FCO) and flash pyrolysis (FPY) conditions showed that FCO is a more thermally reactive and resource efficient process resulting in a higher mass loss ($M_L$), but lower residual mass ($R_M$) compared to FPY. Overall, the results indicate that combustion is a potentially practical route for future effective energy recovery from DDG.

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