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Fuel Quality and Energy Recovery Analyses of Duduguru Coal from the Middle Benue Trough, Nigeria

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Abstract

In this study, we explored and examined the fuel quality and energy recovery potential of the recently discovered Duduguru coal (DDG) from the Middle Benue Trough, Nigeria. DDG is a coal resource that warrants investigation to evaluate its properties for future applications. Therefore, its properties are examined through ultimate, proximate, calorific value, and thermal analyses under CO_2-assisted isothermal conditions. To the best of the authors' knowledge, this is the first study to conduct a comprehensive physicochemical and thermal characterisation under CO_2-assisted isothermal thermogravimetric analysis (TGA). CO_2 utilisation as a purge/process gas during TGA is a novel approach to carbon capture and utilisation in Nigerian coal research. The results showed that DDG contains high carbon (~64%), oxygen (~28%), and fixed carbon (~53%) content, with relatively low nitrogen (< 1.5%) and sulphur (< 1%). Notably, the DDG calorific value (~28 MJ/kg) is higher than other coals previously investigated in Nigeria. Thermal analysis demonstrated that DDG coal experienced thermochemical decomposition via a two-stage degradation process of moisture removal (i.e., drying) and volatile matter degradation (i.e., devolatilisation). The findings indicate that DDG is a high-volatile bituminous coal with potential applications as a high-quality fuel, feedstock, or raw material for various applications. The research presented valuable insights for policymakers and engineers to develop an energy economy based on DDG coal.

Keywords: *Fuel characterisation; Energy recovery; Duduguru coal; Nigerian coals; Coal conversion.*

1. Introduction

Coal is a brown-to-black, carbon-rich, and energy-dense sedimentary rock formed from years of geochemical reactions in the earth's crust [1]. Over the years, humanity has evolved various innovative ways to explore and exploit coal for multiple applications such as energy generation [2-3], steel manufacturing [4-5], chemical fuels [6-7] and functional materials production [8-9], among others. Such applications have made coal an important, versatile, and indispensable raw material and feedstock [10-11]. The versatility of coal is also largely due to its abundance, accessibility, and acceptance as a fuel, chemical, and material feedstock [12-14]. More importantly, coal can be found across the globe from the Americas, Africa, European, Australian, and Asian continents [15], which catalyses socio-economic growth and development [16-17].

The recent discovery of large deposits of coal in many parts of Nigeria could rekindle interest in its utilisation for various applications [18-19]. In particular, coal conversion and utilisation for electric power generation is considered the panacea for the energy crises facing many nations [20-21]. Currently, Nigeria experiences constant blackouts, load shedding, and unreliable supply [22-23], which hamper and exacerbate the problems faced by households and businesses in the country [24]. The incessant blackouts have resulted in overdependence on alternative power sources such as generators [25], which generate large carbon dioxide (CO_2) and other greenhouse gas emissions [26]. Given this, researchers have proposed the development of coal power plants [27] based on the nation's abundant supply of coal that is found across all the geo-political zones [20].

It is estimated that Nigeria has > 2.75 billion tonnes of inferred coal reserves [28], whereas ~640 million tonnes are proven reserves distributed across the nation's sedimentary basins [29]. Large proportions of these are found in the Middle Belt Trough (MBT) region of the country [30-32], particularly in Nasarawa State, which is also rich in solid minerals [33]. The discovery of coal deposits in Duduguru village in Obi Local Government Area of Nasarawa State presents opportunities for multi-sector applications, such as electricity power generation [30,32]. However, the lack of comprehensive data on the characteristics of coal has repeatedly been cited as a factor hampering its utilisation in Nigeria [27,34]. Studies by various experts have shown that the physical, chemical, thermal, microstructural, and mineralogical properties of coal are necessary to design, develop, and deploy coal-fired electricity [35-36]. Such studies elucidate and highlight the nature, rank, energetic and fuel properties of coals, which are crucial to coal power systems and energy generation technologies [37-38].

Therefore, the current study seeks to examine the fuel quality and energy recovery properties of DDG coal from the MBT, Nigeria. As one of the newly discovered coals in Nigeria, it is expedient for experts to explore and examine its fuel properties and energy recovery potential. The study will, thus, characterise the physicochemical and energetic fuel properties of DDG coal using ultimate, proximate, and calorific values as well as thermal analyses under CO_2-assisted isothermal conditions. The novelty of the study also lies in the use of CO_2 as a purge/process gas for thermal analysis of DDG coal. We believe the study adds vital knowledge to the carbon capture and utilisation dimension of coal research in Nigeria. It is envisaged that the study will inform policymakers and assist engineers in developing an energy economy based on DDG coal.

2. Materials and methods

2.1. Sample preparation

The Duduguru (DDG) coal sample was obtained from Duduguru village in Obi Local Government Area of Nasarawa State from the Middle Belt Trough (MBT) sedimentary basin of Nigeria. The rock samples of DDG coal were bagged and transported to the laboratory for further analysis. Before analysis, the rock samples were crushed/pulverised and sieved using a dry miller (Model: Panasonic 400 MX Grinder, Malaysia) and laboratory sieve (Mesh size 60 WS Tyler, USA), respectively, to obtain uniform-sized particles < 250 microns. All tests were performed at the Hydrogen and Fuel Cell Laboratory located at the Johor Bahru campus of the University of Technology, Malaysia.

2.2. Physicochemical and calorific analysis

The physicochemical characterisation of carbonaceous materials such as coal is an important prerequisite for thermal conversion and energy utilisation. In this study, the physicochemical analysis of DDG coal was performed to examine its elemental, proximate, and calorific properties. For the elemental analysis, the powdered coal sample was analysed to determine its elemental composition comprising carbon, hydrogen, nitrogen, and sulphur (CHNS) using the CHNS analyser (Model: vario MACRO Cube Analyser, Germany), whereas the oxygen content was determined by difference. The proximate analysis was performed based on the ASTM D3173-75 standards using a muffle furnace (Model: Ney Vulcan D-130, USA) to determine the moisture, ash, and volatile matter composition. The calorific value (i.e., higher heating value, HHV) was determined using the bomb calorimeter (Model: LECO AC350, United Kingdom).

2.3. Thermal analysis

The energy recovery potential of DDG coal was examined through thermal gravimetry analysis (TGA) under carbon dioxide (CO_2) gas flow and isothermal conditions. The pulverised DDG coal sample was placed and weighed in an alumina crucible before each test. For each test run, approximately 16.44±0.14 mg of sample was placed in the TGA analyser (Model: Shimadzu TG-50, Japan) before purging with CO_2 at a flow rate of 100 mL/min. The energy recovery potential analysis under carbon dioxide (CO_2) assisted thermal gravimetry analysis (TGA) occurred in two stages, I and II. The first stage involved heating the coal sample from 26 °C to 105°C at the heating rate of 30°C/min, followed by a hold time of 5 mins. The second heating stage occurred from 105°C to the required TG test temperature of 650°C, 750°C, or 850°C at a heating rate of 30°C/min and holding time of 30 mins. Stage I was performed to effectively dry the coal sample before analysis of its energy recovery potential under CO_2-assisted isothermal TGA conditions.

On completion, the mass loss (TG, %) and derivative mass loss (DTG, %/min) data were recovered from the thermal analysis software (Version: Shimadzu Workstation TA-60WS). The raw data was processed and plotted against temperature (°C) and time (mins) to examine the thermal profiles, degradation behaviour, and potential reaction pathways of DDG under CO2-assisted isothermal TGA conditions. Next, the temperature profile characteristics (TPCs) comprising the ignition (Ti), midpoint (Tm), burnoff (Tf), and peak decomposition (Tp) temperatures alongside mass loss (ML, %) and residual mass (RM, %) were determined from the TG/DTG data.

3. Results and discussion

3.1. Physicochemical characteristics

Table 1 presents the ultimate analysis, proximate analysis, and calorific value analysis results of the DDG coal sample from the MBT of Nigeria. The results are presented on a dry ash-free and dry basis, although it is important to state that the as-received moisture content of DDG is 6.54%. As observed in Table 1, DDG contains high C (64.11%) content, which acts as the key energy source for energy recovery. The C content in coal plays an important role in energy recovery through thermochemical conversion technologies such as pyrolysis and combustion [39]. The results also show that DDG contains high oxygen (O, 27.92%), which could be detrimental to energy recovery during conversion. Studies report that high O content is also damaging to coal HHV [40] and contributes to higher emissions of greenhouse gases like CO_2 [41].

Table 1. Physicochemical properties of DDG Coal.

Analysis	Elements/Fuel Property	Symbol	DDG coal
Ultimate*	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**	Volatile Matter	VM (wt.%)	35.33
	Ash	A (wt.%)	11.87
	Fixed Carbon	FC (wt.%)	52.81
Calorific	High Heating Value	HHV (MJ/kg)	28.41

**Dry ash free; **Dry basis*

The presence of N and S in coal is an indication of the potential NOx and SOx formed during thermal conversion. The ultimate analysis revealed that the N and S of DDG are 1.39% and 0.67%, respectively. The findings indicate that N is reasonably low, which could help mitigate its oxidation by excess oxygen during combustion to produce nitrogenous oxides (NO_x). On the other hand, the presence of S has the potential to generate sulphurous oxides (SO_x), which are major waste products from burning coal. Overall, the ultimate analysis shows that DDG has good fuel characteristics due to its high content of combustible elements and relatively low pollutant elements. Hence, it could be considered a good-quality fuel, raw material, or feedstock for coal combustion.

The proximate analysis reveals that DDG has a VM and FC content of 35.33% and 52.81%, respectively. The VM indicates that DDG can be readily ignited to recover energy via combustion or transformed into other useful carbon-based products such as char and coke via pyrolysis or carbonisation. DDG also contains 11.87% ash, which indicates that it could generate high quantities of non-combustible residual and mineral material during combustion. High ash content can hamper fuel ignition, decrease fuel output, and trigger slag or clinker formation during high-temperature coal combustion [39,42]. Ultimately, these could increase operational costs due to the challenges of ash waste management. The calorific value analysis revealed that DDG has a reasonably high energy content based on its HHV of 28.41 MJ/kg. Comparatively, DDG has a higher HHV than several other Nigerian coals, such as Enugu (11.43 MJ/kg), Okaba (27.92 MJ/kg), Lafia-Obi (26.24 MJ/kg), and Lamja (27.16 MJ/kg) [36]. Hence, DDG can generate significant quantities of energy when combusted for energy recovery.

The fuel quality of coal is also determined by its rank or classification. The most commonly adopted criteria used to examine coal quality and rank is based on the ASTM 388 standard [43-44]. Based on the standard, DDG is categorised as a low-rank and high-volatile bituminous coal due to its VM (~35%) and HHV (~28.41 MJ/kg) contents. Based on the above, DDG coal is a quality fuel, feedstock or raw material for generating thermal power, large-scale heating, and coke production for the steel industry. It could also be utilised as fuel in furnaces and boilers in electric power generation plants or as a blending component for enhanced co-combustion.

3.2. Thermal analysis

The potential for energy recovery from DDG coal was examined through CO2-assisted thermal gravimetric analysis under isothermal conditions. The mass loss-temperature plots for DDG coal thermal degradation under CO_2-assisted isothermal conditions are presented in Figure 1.

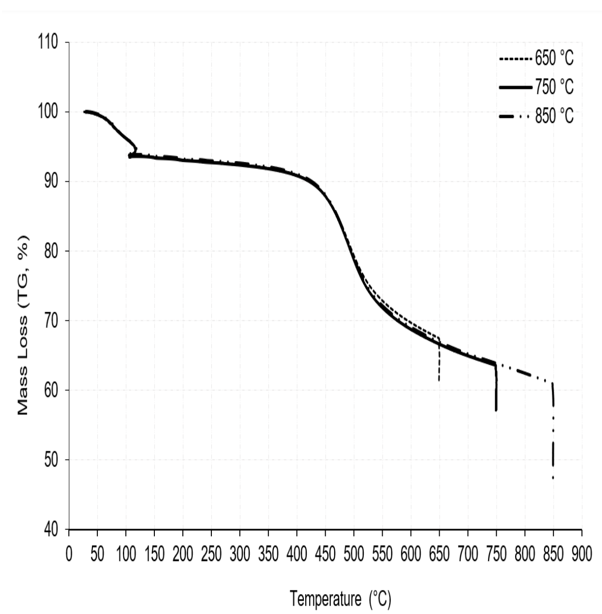

Figure 1. Mass loss - Temperature plots for DDG coal under CO_2 assisted Isothermal conditions.

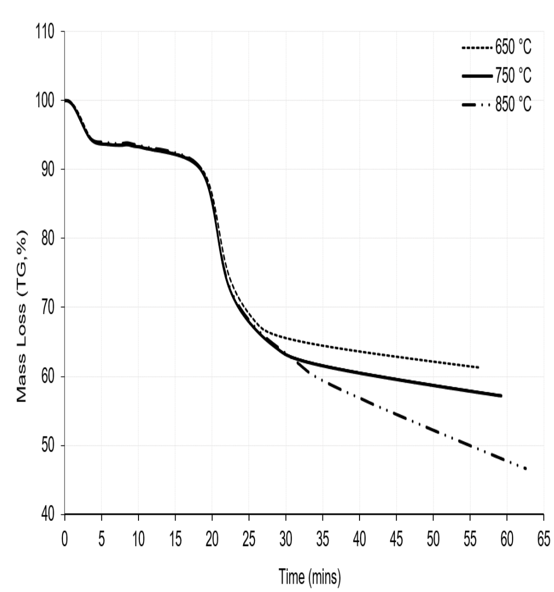

Figure 2. Mass loss - Time plots for DDG coal under CO_2 assisted Isothermal conditions.

As observed in Figure 1, DDG experienced mild but gradual thermal degradation from room temperature to 105°C, followed by more rapid degradation until the end of the process at each temperature at 650°C, 750°C, and 850°C. In Fig. 2, it could be observed that the duration of the isothermal TGA process increased with higher temperatures, which indicated longer times reaction times. This suggests that the degradation of DDG coal occurs at different rates owing to TGA conditions. Next, the temperature profile characteristics (TPCs) of DDG coal during the TGA degradation process were examined. The TPC analysis provides insights into the thermal degradation and decomposition behaviour of coals [21]. Figure 2 presents the mass loss-time plots for DDG coal thermal degradation under CO2-assisted isothermal conditions.

Table 2 presents the TPCs for DDG coal examined in this study. The TPCs examined in this study are the ignition (Ti), midpoint (Tm), peak decomposition (Tp), and burnoff (Tf) temperatures, along with the mass loss (ML, %) and residual mass (RM, %) as elucidated from the TG/DTG data. For all cases, the TPC values were found to increase with increasing TGA temperature from 650°C to 850°C. On average, the values of the TPCs were Ti = 397.61°C, Tm = 501.72°C, and Tf = 597.93°C. The findings indicate that the thermal degradation of DDG could be optimised between 400°C and 600°C for effective energy recovery during thermal conversion.

The average values for the ML and RM were 45.02% and 54.98%, respectively. Based on the ML and RM data, the thermal degradation of DDG coal during the TGA process results in average mass losses of 45.02%, which suggests that 54.98% is solid coal char or ash materials. Coal char is the carbon-rich product generated from pyrolysis or partial combustion [45], which typically occurs at varying temperatures between 300°C and 600°C [46]. It is widely utilised as a fuel or feedstock for producing activated carbons and additives in metallurgical processes [47-48]. On the other hand, coal ash is the by-product of inorganic waste generated from coal combustion [49]. It is typically categorised as fly, bottom, or boiler slag [50-51]. However, it is considered "scheduled waste" due to its toxic constituents [52], such as metallic inorganic or oxide-based compounds [53], which pose grave public health and environmental risks if improperly handled.

Table 2. Temperature characteristic profiles for DDG coal.

Temperature (°C)	Temperatures (°C)			Mass loss (ML, %)	Residual mass (RM, %)
	Ignition (Ti),	Midpoint (Tm),	Burnoff (Tf)		
650	396.04	490.51	580.37	38.69	61.31
750	398.06	496.76	589.41	42.94	57.06
850	398.73	517.88	624.02	53.43	46.57

The thermal degradation pathway for the CO_2-assisted degradation of DDG coal under isothermal conditions was also examined in this study based on the derivative mass or DTG plots. Figure 3 shows the derivative mass loss-temperature plots for DDG coal, whereas Figure 4 shows the derivative mass loss-time plots. As observed, the DTG plots reveal two degradation peaks occurring in the temperature ranges between room temperature and 105°C and between 200°C and the final TG temperatures of 650 °C, 750 °C, and 850 °C. The smaller peak observed from RT-105°C (Fig. 3), which marks the first stage of the degradation, was characterised by mass losses between 6.02-6.31% (on average 6.20%). The mass loss in this temperature range is within the range reported for the moisture content (M = 6.54%) of DDG. This finding suggests that thermal degradation during this stage is due to the removal of surface moisture [54], which is termed drying or dehydration [55]. Studies have shown that coal contains moisture, albeit in quantities, depending on the coal rank [39].

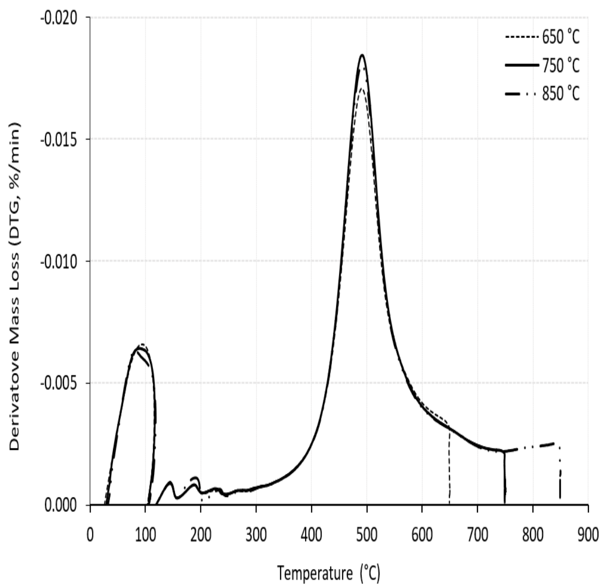

Figure 3. Derivative mass loss - temperature plots for DDG coal under CO_2 assisted isothermal conditions.

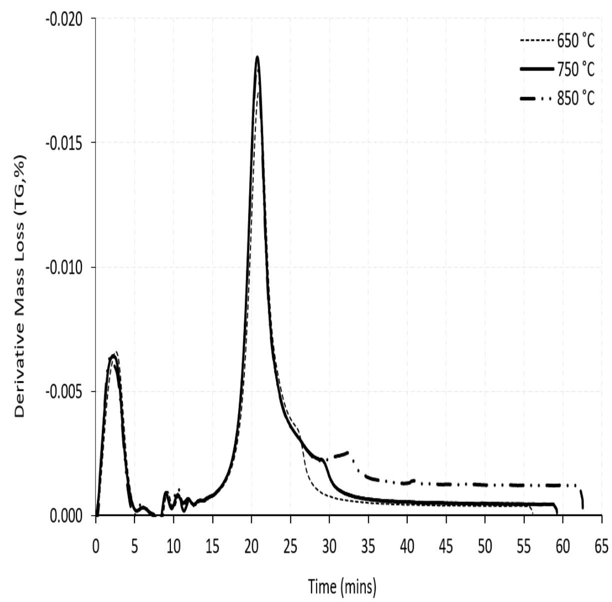

Figure 4. Derivative mass loss - time plots for DDG coal under CO_2 assisted Isothermal conditions.

The second stage, marked by the larger peaks, resulted in significant mass losses from 28.16-30.69% (or 29.83% on average). The observed loss is within the range of values for volatiles (35.33%) reported for the coal in Table 1. As such, it could be reasonably inferred that the degradation of DDG in this stage of the process could be ascribed to the degradation of volatile matter in the coal. The ML values were found to increase with increasing TGA temperatures from 650°C to 850°C, which suggests that higher temperatures increase the evolution of volatile gases. The practical implication is that the high-temperature devolatilisation of coal is critical to improving the processing of coal for the production of energy, materials, and utilisation in industry processes.

4. Conclusions

The study examined the fuel quality and energy recovery potential of Duduguru coal from the Middle Benue Trough of Nigeria. The physicochemical studies of DDG revealed high carbon, hydrogen, oxygen, and fixed carbon but relatively low nitrogen and sulphur contents. The calorific value of DDG coal was found to be higher than that of other coals previously examined in Nigeria. The CO2-assisted thermal analysis revealed that DDG readily undergoes thermal decomposition through a two-stage degradation pathway that consists of removal of moisture (drying) and degradation of volatile matter (devolatilisation). This finding also suggests that the use of CO2 during DDG coal conversion is a viable approach to valorising this troublesome GHG and demonstrating its capture and utilisation potentials for future industrial applications. Overall, the findings reveal that DDG coal is a high-volatile bituminous coal that could be utilised as a quality fuel, feedstock or raw material for generating thermal power, large-scale heating, and coke production for the steel industry.

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