Fuel Characterization of Newly Discovered Nigerian Coals

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Abstract. This study seeks to characterize and highlight the fuel properties, rank, and classification of coals from *Ihioma* (IHM) and *Ogboligbo* (OGB) in Imo and Kogi states of Nigeria, respectively. The fuel properties were examined based on ultimate, proximate, and bomb calorific analyses. The results indicated that IHM coal contains comparatively higher C and H but lower O, N, and S content than OGB. In addition, the nitrogen (N) and sulphur (S) content for both coal samples were above 0.7 wt.% and 1.5 wt.%, respectively, which indicates high potential for pollutant emissions. Furthermore, the coal proximate properties were below 5 wt.% for *Moisture*; *Volatiles* (70 wt.%); *Fixed Carbon* (45 wt.%) and Ash (2.5 wt.%) on average. IHM coal has an HHV of 19.40 MJ/kg whereas OGB is 15.55 MJ/kg. This is due to the low carbon (C), hydrogen (H) and high oxygen (O) content in OGB whereas IHM contains higher *VM* and *HHV*. Furthermore, OGB presents better handling, storage, and transport potential. Furthermore, OGB has a higher fuel ratio and value index due to lower moisture, ash content, and volatiles. Based on the ASTM D388 standard, the coals were classified as Lignite (Brown) Low-Rank Coals (LRCs) with potential for energy recovery.

1. Introduction

Coal utilization presents significant potential for the energy recovery and power generation necessary for socio-economic growth and sustainable development [1]. The availability, accessibility, and acceptability of coal resources are key dynamics in the global quest for low-cost, secure energy supplies for the future [2, 3]. As a result, the discovery of new deposits in developing countries like Nigeria has rekindled interest in coal energy economy [4, 5]. However, lack of comprehensive data on the physicochemical, thermal kinetic, and thermodynamic coal properties is currently hampering transition to coal energy [6]. Coal data is vital to process design, optimization and scale-up of future power plants and conversion systems for efficient utilization [7, 8]. In addition, it can provide

important information required by national policy makers and engineering professionals for evaluating the socioeconomic prospects and environmental impacts of future coal energy systems.

Currently, coal-fired power plants account for 41% of global electric power generation which is derived primarily from lignite (brown) coal utilization [9, 10]. Furthermore, lignite accounts for 80% of coal-based electricity generation in Germany, China, Russia, Poland and Australia [11], although IEA (International Energy Agency) reports that production declined from 834–807.4 Mt/yr from 2013 to 2016 [12].

Despite the global decline, the affordability, reliability, and versatility of lignite coal can stimulate socioeconomic growth, sustainable development, and poverty eradication in developing countries like Nigeria with large new deposits. However, coal utilization for energy recovery, fuel synthesis, and chemicals production is non-existent in Nigeria – Africa's largest economy and most populous nation [13, 14]. This is partially due to resistance from policy, academic and environmental stakeholders to the development, adoption, and implementation of coal despite Nigeria's perennial energy crises. In addition, it is due to concerns about pollutant emissions, global warming, and climate change arising from potential coal utilization [15]. However, the comprehensive characterization of coal fuel properties and implementation of clean coal technologies (CCT) can address the socioeconomic and environmental challenges [16] which currently hamper coal-based electric power generation [17-19]. Therefore, it is pertinent to identify, examine, and highlight coal fuel properties particularly in developing countries like Nigeria with vast new deposits. This will avail scientists, engineers, and policymakers with critical information required to foster the sustainable transition to future coal energy production.

Consequently, this study seeks to characterize the fuel properties, rank classification and potential applications of *Ihioma* (IHM) and *Ogboligbo* (OGB) coal from Imo and Kogi states in Nigeria, respectively. The elemental and calorific fuel properties of the coals based on ultimate, proximate, and bomb calorific analyses will be examined. It is envisaged that the results of this study will provide requisite design and optimization data for future thermochemical coal conversion.

2. Experimental

The coal samples from *Ihioma* (IHM) in Imo State and *Ogboligbo* (OGB) from Kogi State in Nigeria were acquired from the National Metallurgical Research and Development Centre (Jos, Nigeria). Next, the samples were pulverized and sifted using the Retsch™ analytic sieve of mesh size 60 to acquire 250 μm sized particles prior to characterization.

The pulverized coal samples were subsequently characterized by ultimate, proximate, and bomb calorific analyses to examine the fuel characteristics required for rank classification. The ultimate analysis was determined using a CHNS elemental analyzer (Model: vario MICRO Cube™, Germany). The analysis was carried out in duplicate, according to the ASTM D5291 standard and the results were analyzed using the CHNS analysis software (*version* 3.1.1). The proximate analysis was examined by thermogravimetric (TG) analysis based on the procedure described in the literature [20].

The calorific (higher heating) value was determined using a bomb calorimeter (Model: IKA C2000, USA) according to ASTM D2015 whereas the lower heating value (LHV) were calculated as described by Eq 1 from literature [21]. The mineral matter (*Mm*) content of the fuel was calculated from the *Parr* formula described in the literature [10].

$$LHV = HHV - (22.604 \times H) - (2.581 \times MC) \tag{1}$$

$$Mm = (1.08 \times AC) + (0.55 \times S) \tag{2}$$

The terms in Eqs 1 and 2 represent *LHV* – Lower Heating Value (MJ/kg); *HHV* – Higher Heating Value (MJ/kg); *H* – Hydrogen content; *MC* – Moisture content; *Mm* – Mineral Matter; *AC* – Ash and *S* – Sulphur content. Lastly, the rank classification of the coals was examined according to the procedures of the ASTM D388 standard [22].

Based on the ultimate and proximate analyses of the IHM and OGB coal samples, the atomic and fuel property ratios were determined based on relations;

Lower Heating Value $\qquad$ $LHV = HHV - (22.604 \times H) - (2.581 \times MC)$ (3)

Mineral Matter $\qquad$ $Mm = (1.08 \times AC) + (0.55 \times S)$ (4)

Combustible to Pollutant Ratio $\qquad$ $\dfrac{C + H}{N + S}$ (5)

Heating Value to Pollutant Ratio $\qquad$ $\dfrac{HHV}{N + S}$ (6)

Heating Value to Combustible $\qquad$ $\dfrac{HHV}{C + H}$ (7)

Fuel Ratio $\qquad$ $\dfrac{FC}{VM}$ (8)

Fuel Value Index $\qquad$ $\dfrac{HHV}{AC + MC}$ (9)

The atomic and fuel value ratios for the IHM and OGB coal samples are presented in Tables 2 and 4 as deduced from the Ultimate and Proximate analyses in Tables 1 and 3, respectively.

3. Results & Discussion

3.1. Elemental Analysis

The elemental composition of IHM and OGB coal is presented in Table 1 on a comparative basis with other coals in the literature [23]. As observed in Table 1, the *H, N, S* values for the coal samples examined in this study are in good agreement with values in literature. However, the *C* and *O* values are markedly different due to the typical variation in the fuel properties of different ranks of coals [10].

Table 1. Ultimate Analysis of IHM and OGB coal samples

Fuel Property	Symbol	IHM Coal (wt.%)	OGB Coal (wt.%)	Coal Values [23]
Carbon	C	46.87	37.33	62.9–86.9
Hydrogen	H	5.33	3.44	3.5–6.3
Nitrogen	N	0.66	0.81	0.5–2.9
Sulphur	S	1.50	2.27	0.2–9.8
Oxygen	O	45.64	56.15	4.4–29.9
Higher Heating Value	HHV (MJ/kg)	19.40	15.55	16.0–34.0
Lower Heating Value	LHV (MJ/kg)	18.32	14.85	**

As observed in Table 1, the *C* content in IHM is 46.87 wt. % whereas OGB is 37.33 wt.%. The *H* content is 5.33 wt. % in IHM and 3.44 wt.% in OGB coal. The *O* content in the coals is 45.64 wt.% for IHM while OGB is 56.15 wt.%. Lastly, the nitrogen (*N*) and sulphur (*S*) content for both coal samples is above 0.70 wt.% and 1.50 wt.%, respectively. The *N* and *S* content indicate that thermal conversion and utilization of IHM and OGB may be detrimental to the environment due to the potential risk of gaseous pollutant emissions. However, this can be potentially addressed by implementing clean coal technologies such as carbon capture and storage (CCS) or co-firing in biomass fuels for sustainable energy recovery and reduction of carbon footprint [24]. Comparatively, IHM contains higher proportions of *C* and *H* but lower *O, N,* and *S* content than OGB.

Likewise, the calorific (HHV) value of IHM (19.40 MJ/kg) is higher than OGB coal (15.55 MJ/kg). This is due to the higher proportions of the key combustible elements; C and H in IHM. The calorific value of coal is considered one of the most important factors for assessing energy recovery potential for electricity generation in power plants [25]. Furthermore, it is an important dynamic for evaluating the operational thermal efficiency [26] and engineering economics of coal-fired power plants [27]. Typically, the heating value requirement of coal in power plants ranges from 9.50 – 27.00 MJ/kg [25].

Therefore, IHM and OGB are potentially viable feedstock for energy recovery and electricity generation in future coal-fired power plants. The results also reveal that the thermal conversion of IHM coal will potentially result in higher net energy production which indicates it is of higher quality compared to OGB. Based on the ultimate analysis in Table 1, the atomic ratios of the coal samples were calculated as presented in Table 2.

Table 2. Atomic Ratios for IHM and OGB coal samples

Fuel Property	Symbol	IHM Coal (wt.%)	OGB Coal (wt.%)
Hydrogen/Carbon	H/C	0.11	0.09
Oxygen/Carbon	O/C	0.97	1.50
Nitrogen/Carbon	N/C	0.01	0.02
Combustible to Pollutants Ratio	C+H/N+S	24.17	13.24
Heating Value to Pollutants Ratio	HHV/N+S	8.98	5.05
Heating Value to Combustibles Ratio	HHV/C+H	0.37	0.38

The findings in Table 2, indicate that the atomic ratios H/C, O/C and NC were between 0.09 to 0.11, 0.97 to 1.50, and 0.01 to 0.02 for the coal samples. The lower ratios of IHM account for its higher calorific value (MJ/kg) compared to OGB based on the *van Krevelen* relation [28].

Furthermore, the factors; Combustible to Pollutant Elements (CPE) Ratio, Heating Value to Pollutant Elements Ratio and Heating Value to Combustible Elements Ratio of the coal samples were deduced from the ultimate analysis. The CPE ratio is a measure of combustible (carbon, hydrogen) to pollutant elements (nitrogen and sulphur) in the coal samples. However, the Heating Value to Pollutant Elements (HVP) Ratio is a measure of the calorific heating value of the coal sample to the nitrogen and sulphur.

Lastly, the Heating Value to Combustible Elements (HCE) ratio is a measure of the calorific to the combustible elements ratio. As observed, the CPE and HVP values of IHM are higher than OGB coal. However, the HCE of OGB is marginally higher than IHM coal. Overall, the results indicate that energy recovery from IHM coal will emit potentially lower pollutants.

3.2. Proximate Analysis

The proximate and calorific analyses of IHM and OGB are presented in Table 3 in terms of Moisture (MC), Volatiles (VM), Fixed Carbon (FC), and Ash (AC) content along with the calculated values for fuel ratio and mineral matter. As observed, the MC of IHM is 4.75 wt.% whereas OGB is 3.21 wt.%. The VM, FC and Ash content of IHM are 69.52, 23.30 and 2.43 wt. %, respectively. Conversely, the VM, FC and Ash content of OGB coal is 51.43, 44.41 and 1.03 wt.%, respectively.

The results indicate the average values were below 5 wt.% for MC; 70 wt.% for VM; 45 wt.% for FC and 2.5 wt.% for AC. Overall, the values are in good agreement with values typically reported in the literature [23]. In comparison, the MC, VM, AC and *Mm* of IHM are higher than OGB coal although the FC and fuel ratio of OGB is higher than IHM coal.

The Moisture Content (MC) is an important parameter for handling, storage, and transport (HST) of coal. In addition, it is an indicator of the heat energy potential or operational costs required to dry, co-fire, or convert coal in power plants [10]. Based on the results of the coals, the lower MC of OGB indicates its HST costs are potentially lower than IHM coal.

Table 3. Proximate Analysis and Calorific Values of IHM and OGB coals

Fuel Property	Symbol	IHM Coal (wt. %)	OGB Coal (wt. %)	Coal Values [23]
Moisture	MC	4.75	3.21	0.4–20.2
Volatiles	VM	69.52	51.43	12.2–44.5
Ash	AC	2.43	1.03	5.0–48.9
Fixed Carbon	FC	23.30	44.41	17.9–70.4
Mineral Matter	*Mm*	3.45	2.36	**

The Volatile Matter (VM) significantly influences the thermochemical reactivity, rank classification, and conversion efficiency of coal [28, 29]. In addition, it is a measure of condensable and non-condensable volatile compounds generated from the thermal decomposition of coal under given reaction conditions [10]. The lower VM of OGB coal also indicates better storage potential and low potential for spontaneous combustion compared to IHM. However, the higher VM of IHM is better suited for syngas production through pyrolysis and gasification technologies whereas OGB can undergo combustion for energy recovery.

The Ash Content (AC) of OGB was lower than IHM as observed in Table 3. Ash is the non-combustible residual or mineral matter produced from coal combustion. According to *Chukwu et al.,* [1], ash significantly affects waste handling, processing, and utilization equipment. In addition, the chemical composition of ash is a measure of the fouling, slagging and agglomeration potential of coal in conversion equipment [10]. Consequently, lower ash, as observed in OGB, is preferable from a cost and operational perspective.

The Fixed Carbon (FC) is the solid carbonaceous residue from drying and devolatilization typically used to estimate the coke (coking) potential and rank classification of coals [30]. Based on the findings of this study, OGB has a higher potential for coke formation and fuel ratio which is an important factor for metallurgical coal applications, energy recovery, and electric power generation.

Based on the proximate analysis, the Fuel Ratio and Fuel Value Index of the IHM and OGB coals were deduced as presented in Table 4.

Table 4. Fuel Ratios for IHM and OGB coal samples

Fuel Property	Symbol	IHM Coal (wt. %)	OGB Coal (wt. %)
Fuel Ratio	FC/VM	0.34	0.86
Fuel Value Index	HHV/AC+MC	2.70	3.67

The results indicate that OGB has a higher fuel ratio and value index compared to the IHM coal sample. This is due to the higher moisture, ash content and volatile matter content in IHM compared to OGB as presented in Table 3.

3.3. Coal Rank and Classification

The rank classification of the coals was examined according to ASTM D388 [22]. According to the standard, the coals are classified as *Lignite* based on HHVs which are less than 24 MJ/kg [10]. The sub-classification analysis indicates that IHM is *Lignitic* coal class A, whereas OGB is class B. In general, the coal samples are Brown or Low-Rank Coals (LRCs) with non-caking properties. This indicates the coals can be potentially utilized for electric power generation [10], coke blending or co-firing with biomass for energy recovery through pyrolysis, gasification, or combustion.

4. Conclusion

The paper investigated the fuel characteristics, rank classification, and potential applications of *Ihioma* (IHM) and *Ogboligbo* (OGB) coals from Nigeria. The characterization was based on ultimate,

proximate, and calorific analyses. The results indicated the coal samples contain sufficient proportions of combustible elements for various energy recovery, power, and metallurgical applications. The IHM coal exhibited higher calorific properties compared to OGB. Furthermore, the fuel characterization indicated OGB has better handling, storage, and transport capabilities compared to IHM coal. However, IHM contains higher VM and HHV suitable for application in gasification and combustion applications. Furthermore, OGB has a higher fuel ratio and value index due its lower moisture, ash content and volatile matter. The rank classification indicates the coals are Lignite (Brown) Low-Rank Coals (LRCs) with potential for electricity generation or biomass co-firing for enhanced energy recovery and fuels synthesis. Lastly, the coal characteristics presented in this study can be utilized for the design, optimization, and scale-up of future conversion systems for energy recovery.

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