VOL. 12 NO. 2,
MAY, 2026
E-ISSN 3027-1533
P-ISSN 3026-8648

African Scholar Publications & Research International
www.africanscholarpub.com

Journal of African Innovation & Advanced Studies (JAIAS)

Experimental Investigation of the Thermal Performance of Coal–Sawdust Fuel Pellets with Varying Biomass Ratios

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DOI: https://doi.org/10.70382/ajaias.v12i2.082

Abstract

Coal remains a major source of electricity generation; however, its direct combustion poses efficiency and environmental challenges. This study evaluates the thermal performance of coal–sawdust blends prepared in varying mixing ratios, with emphasis on their proximate characteristics, including moisture content, ash content, volatile matter, and fixed carbon. Seven pellet samples (1–7) were produced through mixing coal and sawdust with a resin binder and subsequently subjected to calorimetry tests to determine their calorific values. The results revealed calorific values ranging from 14.85 MJ/kg to 22.07 MJ/kg, demonstrating their potential suitability as alternative fuels for heating applications. The findings indicate that the chemical composition of the blends, particularly volatile matter, ash, fixed carbon, and moisture content, significantly influences their thermal behaviour, including calorific value, ignition time, and combustion rate. Furthermore, the mixing ratios were found to play a critical role in determining the pellets' overall thermal performance. The study suggests that optimizing biomass-to-coal ratios could enhance combustion efficiency, reduce energy costs, and promote more sustainable energy utilization.

Keywords: Biomass Co-firing, Fuel Pellets, Proximate Analysis, Bio-coal Pellet, Renewable Energy, Solid Fuel Combustion.

Introduction

Coal is primarily used as a fuel to generate power in steam engines, factories and electric plants. Coal is mostly carbon with a variable number of other elements, mainly sulphur, hydrogen, oxygen and nitrogen (Blander M, 2011). Sawdust is a primary fuel obtained as a by-product from wood, with unique combustion properties. Sawdust (or wood dust) is obtained from processes such as sawing, sanding, milling and routing of wood. When sawdust is fired together with coal, it has the potential to improve its thermal performance, such as ignition temperature, burnout efficiency and combustion kinetics. Coal is a traditional and mostly used source of energy, and improving its thermal performance has been an area of extensive research. This study delves into augmenting coal combustion with sawdust to maintain coal's thermal performance, reduce carbon dioxide emissions and lower energy costs, since energy is a crucial factor that impacts economic development and, in turn, contributes to the standard of living (Ekpu and Obadina, 2020).

The combustion of a coal-sawdust blend will be examined with respect to its calorific value. The energy density of coal is high, and its cost is higher than that of sawdust. According to the International Energy Agency (IEA), coal will remain a global energy solution throughout the 21st century. The International Energy Agency (IEA) also reported that coal accounted for 16% of the total electricity generated in the United States. This study will help maintain the thermal performance of coal; reduced emissions and the cost of heat energy generation will be drastically reduced due to the introduction of sawdust as an additive. When sawdust is co-fired with coal, it can alter the coal's thermal behaviour and significantly influence emissions. (Erokare *et al*., 2026)

The world energy landscape is undergoing a tremendous transformation, with rapidly increasing emphasis on sustainability, energy efficiency, and reduced environmental impact. Currently, the world's energy demand is largely met by fossil fuels such as coal and natural gas (Akkaya A.V., 2009). Coal demand has increased significantly because of efforts to build new coal-fired thermal power plants (Sivrikaya O., 2014; De-Souza *et al*., 2012). Coal, a traditional and widely used energy source, has been the focus of broad research aimed at improving its thermal performance and reducing its negative environmental impact. The rationale for this research is the urgent need to develop sustainable energy production methods and reduce carbon dioxide emissions associated with coal combustion. Sawdust, a by-product of wood, has become a potential additive to coal due to its renewability and potential for reducing carbon dioxide emissions from coal. According to Erokare *et al*. (2026), when sawdust is co-fired with coal, it alters the thermal characteristics of the coal, thereby affecting parameters such as ignition temperature, emissions, burnout efficiency, combustion kinetics and overall thermal performance. Numerous studies have been conducted to explore the combustion behaviour of coal-biomass blends during burning. The higher the carbon content, the higher the calorific value of coal, since carbon is the combustible constituent of coal

and releases a lot of heat energy when oxidized during combustion. When the carbon content in coal reacts with air (oxygen), carbon dioxide (CO_2), thermal energy and water vapour evolved. The thermal energy liberated per unit mass of carbon is relatively constant. Miranda *et al*. (2025) investigated different pellets, including woody biomass, herbaceous biomass and fruit biomass and reported that the higher the carbon content (percentage) in the pellets, the higher the heating values observed. Obemberge *et al*. (2004) noted that carbon and hydrogen account for the energy content of biofuels due to exothermic oxidation (combustion) reactions. From studies by Spliethoff (2010) and Sadiur et al. (2011), it was observed that as the carbon and hydrogen content of a fuel increase, its calorific value (CV) increases.

The calorific value of a fuel is defined as the quantity of thermal energy liberated when one kilogram of the fuel is completely burned in air (oxygen). Sub-bituminous coal possesses a moderate calorific value. According to (Petel *et al*., 2007) and (Llorente and Garcia, 2008), calorific value is defined as the thermal capacity per unit weight of coal after complete combustion. The thermal performance of a fuel increased with its calorific value. The calorific value of a fuel is expressed in KJ/kg for solids and liquids and KJ/m3 for gases. Usaka *et al*., 2023 investigated the properties of bio-coal briquettes which consist of coal and prosopis African pods (biomass) and reported the range of calorific values of the briquette samples, A (100% Coal 0% Sawdust), B (80% Coal 20% Sawdust), C(60% Coal 40% Sawdust), D(40% Coal 60% Sawdust), E (20%) to be (23.25MJ/kg, 21.12MJ/kg, 18.90MJ/kg, 18.27MJ/kg, 17.02MJ/kg and 16.25MJ/kg) respectively.

Ye *et al*. (2021) investigated the co-combustion characteristics of coal and various biomass fuels. Such as corn straw, rice husk and rice straw, with biomass blend ratios of 20 wt%, 40 wt%, 60 wt% and 80 wt%. The method of thermogravimetric analysis was used to evaluate parameters such as combustion indices, ignition temperature and weight loss. The results from the combustion parameter shown suggest that as biomass is added, the blend's combustion performance improves. Umubigho *et al*. (2025) investigated the combustion of sawdust-coal pellets at varying ratios and their emissions, and reported that blending coal with sawdust biomass can significantly reduce greenhouse gas emissions, including carbon dioxide (CO_2). This research work is critically aimed at determining the effects of moisture content, ash content, volatile matter and fixed carbon content on the thermal behaviour of various sawdust-coal blends having varying mixed ratios

MATERIALS AND METHOD

Pellets (Specimen) Preparation

The Pellets used in this study are made up of sawdust of particle sizes of 1.2 - 2.3mm and coal of particle sizes of 0.9 - 1.10 mm mixed with resin (the polyester type) with a concentration of 35% applied to each pellet's sample. The pellets consist of varying percentages of coal and sawdust. The various pellet specimens, samples 1-7 and their mixed ratios are shown in Table 1 and Figure 1 (a – g). The sun-dried coal particles are evenly mixed with sun-dried sawdust particles. After thorough mixing, the resin is introduced to the mixture. The mixture is then

hand-mixed. Each of the specimens (pellets) is sun-dried at a temperature range of 26 – 300 °C for three (3) days to further reduce moisture content and improve its mechanical strength.

Table 1: Components of Pellet Feedstock

Pellet Samples	Coal (%)	Sawdust (%)
Sample 1	100	0
Sample 2	90	10
Sample 3	80	20
Sample 4	70	30
Sample 5	60	40
Sample 6	50	50
Sample 7	0	100

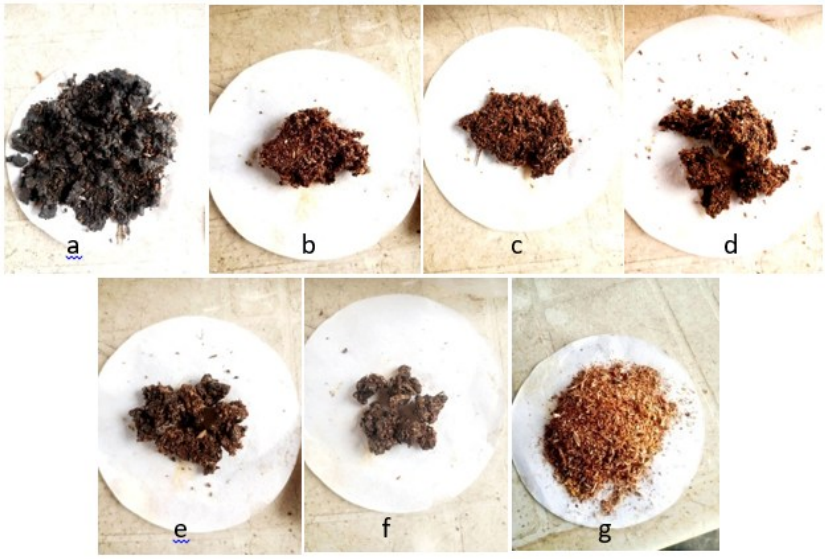


Figure1: (a = sample 1, b = sample 2, c = sample 3, d = sample 4, e = sample 5, f = sample 6 and g = sample 7)

Pellets Calorimetry Test

The determination of the calorific value of each of the pellet samples labelled Sample 1 - 7 was carried out using a bomb calorimeter in accordance with ASTM D5865, an electric oven and a test tube.

The procedure for the determination of the calorific value of the sample is as follows;

i) The sample is weighed using a digital balance (the sample weight should not be more than 1g) to convert the value of the sample, in order to avoid misfire.

ii) The sample is charged into the oxygen (O_2) bomb vessel in which the combustion charges can be burned.

iii) The oxygen bomb vessel was made to fill up with oxygen for the combustion process to occur.
iv) The connecting tube that supplies the oxygen is removed.
v) The bomb containing the oxygen (O_2) and the sample that was connected with an electrode and provides an ignition to a fuse wire was then submerged into the bucket containing water for about 2 litres in the calorimeter.
vi) The electrode is then connected to the vessel directly.
vii) The bomb and the bucket were then held in a calorimeter jacket and served as a thermal shield.
viii) Select the stunt button, the sample ID and the sample weight were inputted and then followed by the bomb ID.
ix) The machine was allowed to run for a duration of about 7minutes for combustion to take place.
x) The displayed unit (MJ/kg) or (Cal/g) depends on which unit the user selected.
xi) The above procedure is repeated for other samples

Proximate Analysis

Proximate analysis helps determine the moisture, volatile matter, fixed carbon and ash content of sawdust-coal pellets. This analysis enables the ranking of sawdust-coal pellets more conveniently and also helps establish the percentage composition of combustible to non-combustible constituents of sawdust-coal pellets. It also provides the basis for evaluating sawdust-coal pellets for various purposes. The proximate analysis is carried out by heating the sawdust-coal pellets to constant weight (ASTM D5865conditions). The following constituents in sawdust-coal pellets are determined separately as follows:

Ash Content

Ash is the non-combustible matter, obtained as the end product of sawdust-coal pellets combustion. A measured weight of sawdust-coal pellets is heated to 700 ± 50 °C in an electric furnace without a lid for 30 minutes. After heating, there is a weight loss in sawdust-coal pellets, and an ash deposit forms. The percentage composition of ash content in the sawdust-coal pellets is obtained using equation 1(ASTM D5142-02, 2002);

$$\text{Percentage of Ash} = \frac{W_{f,ash}}{W_{P,Air}} \; x \; \frac{100}{1} \qquad (1)$$

Where;

$W_{f,\,ash}$ = Weight of ash formed

$W_{P,\,Air}$ = Weight of air-dried sawdust-coal pellets

Moisture Content

A measured mass of 1kg of air-dried sawdust-coal pellets is heated to a temperature of 100 °C – 105 °C using an electric hot air oven for sixty (60) minutes. The weight loss of the sawdust-

coal pellets and the percentage of moisture content is determined using equation (BS EN 14774-1, 2009);

$$\% \text{ of moisture} = \frac{L_P}{W_P}\ x\ \frac{100}{1} \quad (2)$$

Where;
L_P = Weight loss of sawdust-coal pellets
W_P = Weight of sawdust-coal pellets

The moisture content of the pellets determined is essential, as high moisture content in sawdust-coal pellets reduces their calorific value and thermal performance.

Volatile Matter

In this, a crucible with sawdust-coal pellets residue is covered with a lid, and is heated for seven (7) minutes to a temperature of 95 °C ± 20 °C in an electric furnace. The weight loss of the sawdust-coal pellets and the percentage of volatile matter are calculated using equation 3 (ASTM D3175-17, 2017);

$$\% \text{ of volatile matter} = \frac{L_P}{W_P}\ x\ \frac{100}{1} \quad (3)$$

Where**;**
L_P = Weight loss of sawdust-coal pellets
W_P = Weight of sawdust-coal pellets

Fixed Carbon

The fixed carbon content in sawdust-coal pellets is obtained using equation 4 (ASTM E711-87, 2004);

$$\% FCP\ =\ 100\ -\ (VMP + MCP + AshP) \quad (4)$$

Where;
VM_P is volatile matter
MC_P is the moisture content

RESULTS AND DISCUSSION

Calorimetry Test Results of Sawdust-Coal Pellets. The calorific value test results for various percentage compositions of sawdust and coal pellets are shown in Figure 2. The calorific value of the various pellet samples, consisting of Samples 1 -7, was determined in order to ascertain their thermal behaviour as a result of the addition of biomass (sawdust). The test results in Figure 2 show that sawdust addition to coal affects its calorific value, depending on the percentage of sawdust added.

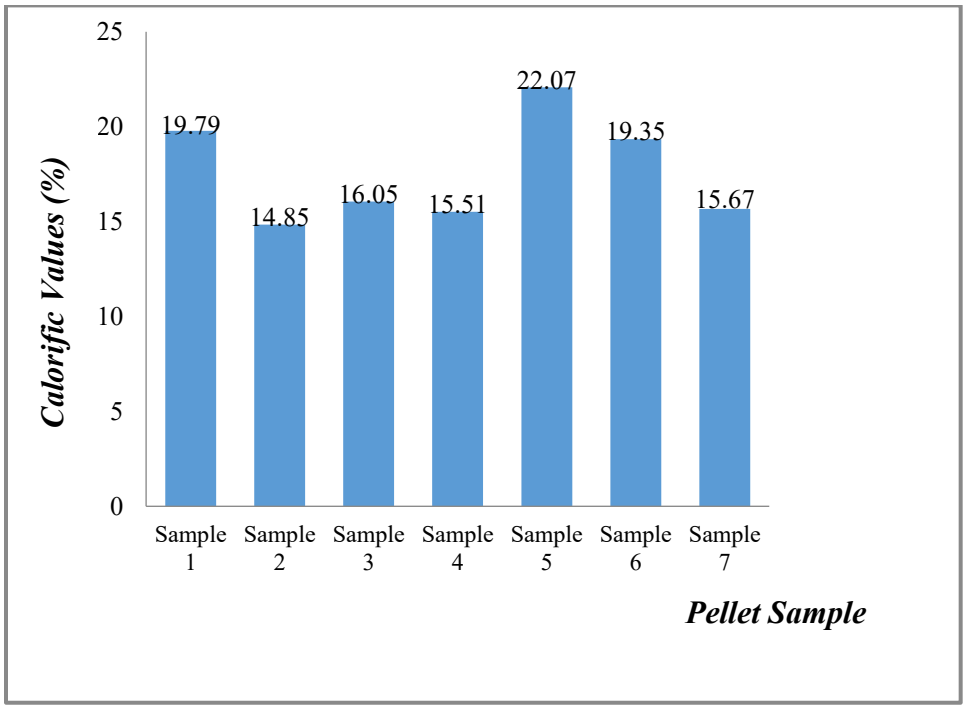


Figure 2: Calorific Values of Sawdust and Coal Blend from Calorimetry

The test results indicated that the blend ratio of sample 5 has a calorific value of 22.07 MJ/kg, while the blend ratio of sample 2 has a calorific value of 14.85 MJ/kg. The highest calorific value of pellet sample 5 can be attributed to its high volatile matter content, compared to the low volatile matter content of pellet samples 1, 2, 3 and 4 and to the higher moisture content of pellet samples 1, 2, 3 and 4. According to Oyeleran and Tudunwada (2015), the calorific value is the determinant of the energy content of the briquette samples, and it is a function of the chemical composition and moisture content of the briquettes. The calorific value results obtained, and shown in Figure 2, are very similar to the range of the calorific values obtained by Chirchir et al., 2013, which is in the range of (25.2 – 26.8 MJ/kg), (11.3 – 14.6 MJ/kg) and (16.10 – 18.50 MJ/kg).

Proximate Analysis Test Result of Pellet Samples

From the results of the proximate analysis test conducted on the various pellet samples 1 to 7, the results obtained are represented in Table 2. From Table 2, it can be observed that pellet sample 6 has the lowest moisture content (2.92%), while sample 7 has the highest (7.82%).

Table 2: Proximate Analysis Results

Parameters	Sample 1 (%)	Sample 2 (%)	Sample 3 (%)	Sample 4 (%)	Sample 5 (%)	Sample 6 (%)	Sample 7 (%)
Moisture Content (M_t)	4.84	4.03	3.96	3.89	3.15	2.92	7.82
Volatile Matter (M_V)	34.60	37.21	40.01	44.90	50.96	57.01	87.54

Parameters	Sample 1 (%)	Sample 2 (%)	Sample 3 (%)	Sample 4 (%)	Sample 5 (%)	Sample 6 (%)	Sample 7 (%)
Ash Content (A_C)	17.00	25.11	28.06	33.20	38.69	35.11	1.86
Fixed Carbon (F_C)	43.56	32.90	27.01	17.90	8.80	4.96	2.78

Effect of Pellets' Moisture Content on Thermal Behaviour

It is observed from Figure 3 that as the percentage composition of sawdust in the pellets decreases, the moisture content also decreases (that is, from 4.03% to 2.92%), and this is consistent with the report of (Okonkwo *et al*., 2017) from the study of proximate analysis and performance evaluation of selected blends of biomass briquettes. The low moisture content in sample 5 pellet contributed greatly to its high calorific value of 22.07 MJ/kg.

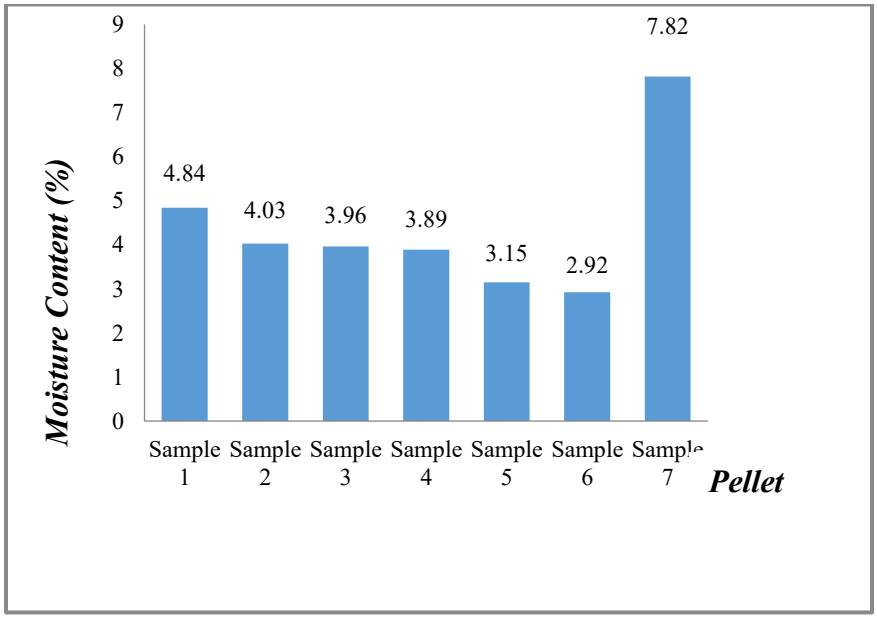


Figure 3: Bar Charts for Moisture Content

The moisture content range (2.92 – 7.82%) of the pellets obtained in this study, shown in Figure 3, agreed with the range (1.03 – 7.11%) reported by Guusu *et al.* (2021) in their study of sesame seed stalk biomass and coal briquettes. According to Usaka *et al.* (2023), a moisture content range of 6-8% in pellets/briquettes indicates they are strong and free of cracks. From the studies conducted by Ikelle *et al*. (2014), Ikelle *et al*. (2017) and Adekunle *et al*. (2015), moisture content was respectively reported to be 2.35 – 5.72% for cassava stalk bio-coal briquettes, 2.78 – 6.95% for a briquette consisting of rice husk, coal, 6.00 – 10.00% for groundnut shell and coal briquette and 5.87 – 7.36% for sawdust biomass and coal briquette, which agrees with the range of the values obtained in this study. According to Huko *et al*. (2015), briquettes having a moisture content greater than 10% are weak and poor.

High moisture content of coal-sawdust pellets significantly contributes to poor thermal performance, such as slow combustion, an increase in ignition time and a reduction in the overall energy output because most of the thermal energy initially supplied to the pellets for combustion to take place will be utilised in evaporation of the moisture contained in the pellets before combustion will start taking place. The range of moisture content obtained in this study suggests that the pellets can be used conveniently as a fuel in various combustion systems, as they burn moderately, ignite quickly and produce reasonable calorific values.

Effect of Pellets' Volatile Matter Content on Thermal Behaviour

From the pellet sample results in Table 2, it is observed that pure coal Sample 1 has the lowest volatile matter percentage (34.60%). It is also observed that pure sawdust Sample 7 has the highest volatile composition, and the composite pellets with the lowest coal content have the highest volatile matter, and the pellet with the highest coal content possesses low volatile matter content. A high volatile matter composition in sawdust-coal pellets contributes greatly to their rapid combustion behaviour, with a high rate of heat release. The above result is similar to the reports of Okonkwo *et al*. (2017). According to Onochie *et al*. (2024), high volatile matter in pellets implies they can be ignited easily.

According to (Efomah and Gbabo, 2015), the volatile matter composition of a fuel determines the amount of smoke produced from the fuel during combustion. Sotande *et al*. (2010 suggested that the presence of low volatile matter in briquettes results in low ignition and a slow combustion process. According to Adekunle (2015), coal with high volatile matter content will generate more smoke.

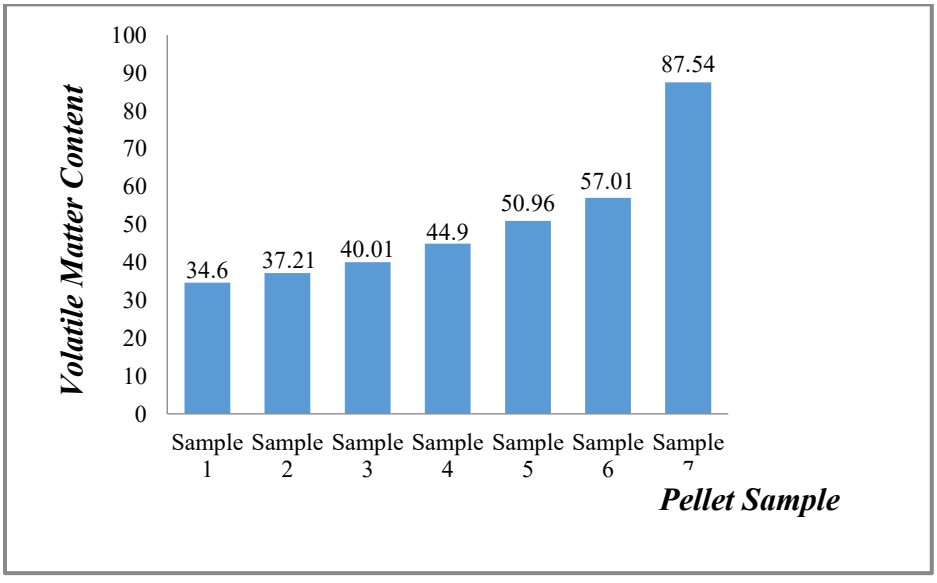


Figure 4: Bar Charts for Volatile Matter

The range of volatile matter composition obtained in this study indicates that pellet samples consisting of coal and sawdust biomass can be ignited easily and used as fuel in heating equipment. The range of the values of volatile matter obtained in this study, as shown in Figure 4, is less than the range of the values reported by Erokare *et al*. (2026), with the exception of Sample 7. But the range of volatile matter values observed in this study is in line with those reported by Yi *et al*. (2017), which range from 4.99 to 47.01%, except for samples 5, 6 and 7, pellets, which have a higher volatile matter composition.

Effect of Pellets' Ash Content on Thermal Behaviour

The results from Figure 5 show that sample 7 has the lowest ash content. It is also observed that the pellet samples consisting of sawdust and coal show an increasing content of ash (that is, from Sample 2 to Sample 5). Generally, the ash content of coal is higher than that of sawdust biomass. The results in Figure 5 show that pellets composed of sawdust biomass and coal have a higher ash content than pure sawdust (Sample 7), in total agreement with the findings of Okonkwo *et al*. (2017).

The value of the ash content of the composite pellets obtained in the range (25.11 - 38.69%) falls within the range (5 - 40%) of boiler ash content percentage specified by the Bureau of Energy Efficiency (BEE).

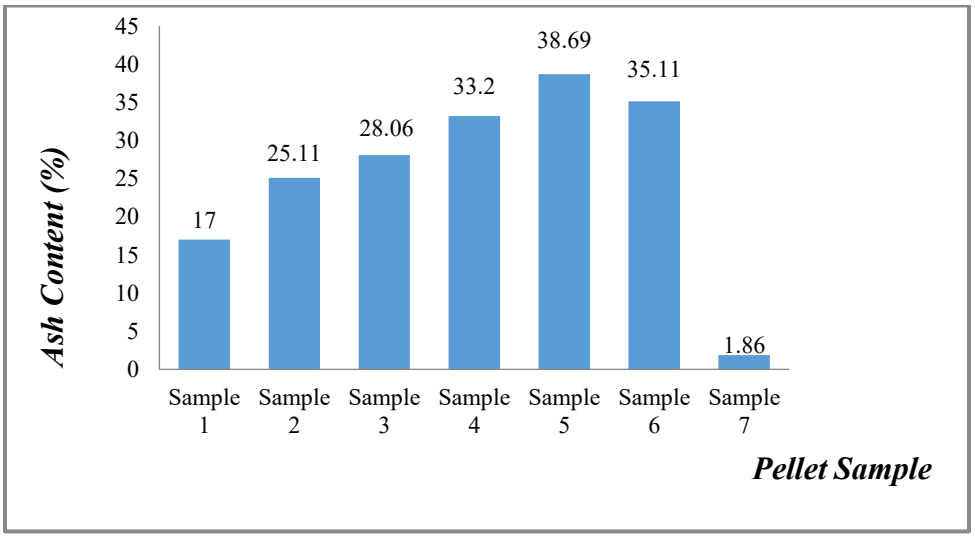


Figure 5: Ash Composition of Pellets

Zolin *et al*. (2001) asserted that ash content has a major influence on the transfer of thermal energy to the surface of boilers and on the transport of oxygen to the surface of a fuel during the combustion of char. Since the ash content range obtained in this study agreed with the BEE report, it suggests that the pellets, which consist of coal and sawdust biomass, can be used as fuel in boiler operations. A high ash content in a fuel indicates a higher proportion of non-combustible materials, leading to lower thermal performance. The high ash content of the fuel

also leads to slagging and clinker formation in the combustion chambers, which subsequently contributes to poor thermal performance.

Effect of Pellets' Fixed Carbon Content on Thermal Behaviour

The general trend of fixed carbon content of the pellets, as shown in Figure 6, shows that the fixed carbon composition decreases with a decrease in coal percentage and an increase in sawdust composition. The trend observed in Table 2 and Figure 6 supports the results of Ye *et al*. (2021) in their study of the co-combustion characteristics of a typical biomass-coal blend using thermogravimetric analysis. From the study conducted by (Peter *et al*., 1988), it was observed that the fixed carbon percentage in the pellet decreases as the percentage of wood in the pellet increases, this therefore shows that the values/trend of the fixed carbon content in the pellet samples is having a strong agreement with the result obtained by (Ye *et al*., 2021 and Peter *et al*., 1988).

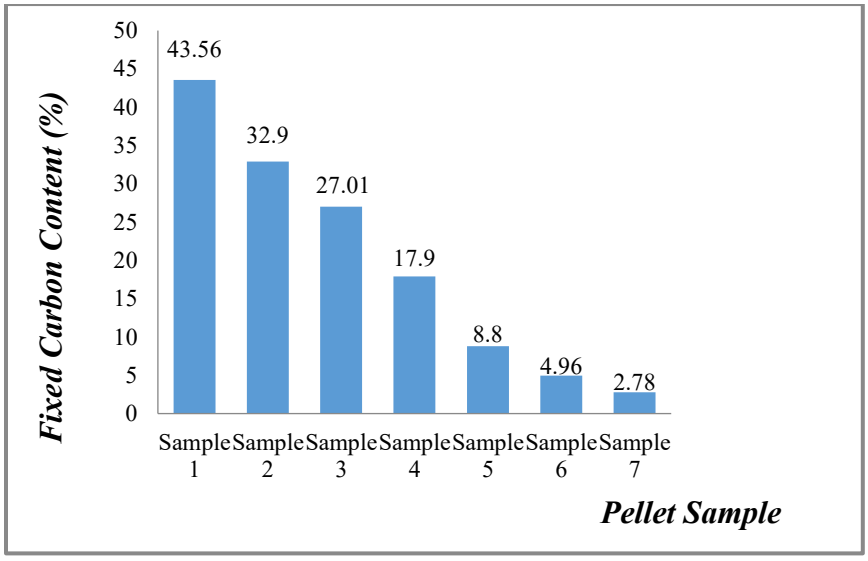


Figure 6: Fixed Carbon Composition of Pellets

Aich *et al*. (2020) asserted that high fixed carbon content does not imply better combustion performance, although an increase in fixed carbon content can initially improve combustion performance. Poor combustion performance can also be attributed to low calorific value and the presence of mineral matter, which can influence the oxidation process of coal (Aich *et al*., 2020).

CONCLUSION

This study has considered in detail the effects of moisture content, ash content, volatile matter content and fixed carbon content on the thermal performance of a sawdust-coal blend. Proximate analysis test and calorimetry test conducted on the various samples, 1 - 7, have revealed that thermal performance, such as calorific values, ignition time and combustion rate

of the blends, is very much dependent on the percentage of the chemical compositions of the pellet samples, such as moisture content, ash content, volatile matter content and fixed carbon content present in the blends. The range of calorific values results obtained from the calorimetry test demonstrated that the sawdust-coal blend is a good fuel for various heating applications.

DECLARATIONS

Competing Interest: The authors declare that they have no conflicts of interest.

Acknowledgments: We wholeheartedly appreciate the contributions of the laboratory staff of the National Steel Raw Materials Exploration Agency, Kaduna, for their technical assistance in the determination of the ultimate and proximate analysis of the sawdust coal pellets samples.

Funding: No funding was received for this research.

Data Availability: All data used in this research work shall be made available upon request.

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