

Characterisation of Briquette Fuel Produced from Admixture of Coconut Coir and Sawdust Particles using Starch Gel binder

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Abstract

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This study investigated the effect of compositional variation on the properties of biomass briquettes produced from the admixture of coconut coir (CC) and sawdust (S) using cassava starch as a binder. The materials were locally sourced and processed to produce five formulations of briquette samples from 100:0 to 50:50 (CC:S) at compaction pressure of 5 MPa and curing temperature at 105 °C for 1 hour. The characterization of the briquettes was done using proximate, ultimate, physical and combustion analysis according to established ASTM standards. Results showed the moisture content of the briquette samples varied from 6.87 to 7.77%, ash content from 3 to 6%, fixed carbon from 11.51 - 14.07% and volatile matter from 74.5 - 76.9%. The Higher Heating Value (HHV) was found to vary from 15.88 - 16.71 MJ/kg. The statistical analysis with one-way ANOVA confirmed significant differences ($p < 0.05$) between different compositions. The briquette sample with 50:50 of coconut coir and sawdust ratio was found to have superior combustion properties with the highest HHV and lowest ash content. The findings demonstrated that optimizing composition and minimizing ash content significantly improves briquette performance. The produced briquette is recommended for both domestic and industrial applications.

1.0 INTRODUCTION

1.1 Background and Motivation

Agricultural biomass residues are a form of biofuel energy that can have a significant effect on greenhouse gas (GHG) emissions if it is properly managed and utilized (Ali *et al.*, 2019). Insufficient usage of agricultural residues or their improper method of disposal mostly cause environmental pollution, thereby posing a health risk and hazard to both man and ecology at large (Adejumo & Adebisi, 2021). Cumulative efforts are geared towards control of pollution, such as conversion of those residues to briquettes. The briquettes provide sustainable energy solution by serving as an alternative to fossil fuels like coal (Kuthe *et al.*, 2021). However, agricultural leftovers in their natural forms may not produce the intended outcome due to their characteristics such as low-density, primarily loose materials, and emission of uncontrollable combustion (Kathuria, 2012). There are many ways and routes by which agricultural residues can be converted to biomass energy. One of the great technological processes is briquetting. Briquetting can be described as a process of compaction of residues under pressure into a product of higher density and volume with high caloric value than the initial materials (Kaliyan & Morey, 2009; Yap *et al.*, 2023). Calorific value (measured as HHV) is one of the most important ways of measuring fuel quality because it determines the amount of heat that is released during the combustion process. Though, the increases in the demands of wood or woody bio-residues for various uses (including the use for production of briquettes) contribute to

deforestation, there are however, many advantages and benefits that could be derived from the use of briquettes over that of firewood due to the following properties: greater heat intensity, cleanliness, convenience in use and reduction in space occupied (Akpenpuun *et al.*, 2020, Alabi *et al.*, 2024; Shalangwa *et al.*, 2024; Oladeji, 2010).

Huge quantities of agricultural and forestry byproducts in Nigeria are grossly underutilized annually, which are typically disposed of through open burning or decompose naturally (Adeleke *et al.*, 2023). Similar issues exist in other developing nations with recent studies confirming coconut residues has not been adequately utilized for energy generation despite its enormous potential (Lavanya, 2026). Agro-residues, like many other combustible materials, are frequently produced either at post-harvest or after use and are more often than not used wastefully or in an unpredictable manner, leading to widespread contamination and becoming a natural threat to society (Nagarajan & Prakash, 2021). However, it has been observed from earlier studies that these rural wastes, including biomass materials such as rice husk, coffee husk, coconut husk, bagasse, groundnut shell, and cotton stalk, are valuable in providing heat energy (Oladeji, 2012). This suggests that they must be compressed through briquetting into a less volume but compacted usable item. The process of densifying free biomass materials by the use of weight to produce small, dense composites of various sizes is known as biomass briquetting. In this manner, residual waste is briquetted using weight, heat, and a knowledgeable expert on unrestricted materials to produce briquettes. This binding agent acting as an adhesive can be any sinewy natural material such as starch, gum, collagen; best bond and so on.

Briquettes are frequently utilized as an advancement intercession to replace firewood, charcoal, or other strong fuels. Within the appropriate context, biomass briquettes can spare time, spare cash, diminish nearby deforestation rates, and give a few pay creating opportunities (Nabukalu, 2021; Kimaro, 2023; Phiri *et al.*, 2025). Nigeria has a lot of biomass residues which are allowed to be wasted and not adequately managed; thus contributes to the nation's environmental pollution (Collins *et al.*, 2022; Okafor *et al.*, 2022; Adeleke *et al.*, 2023). Both organic and inorganic adhesive and binder that are found suitable to bond large amounts of these biomass residues are also readily available in the country (Ogunjobi *et al.*, 2022; Lomunyak *et al.*, 2024; Obi *et al.*, 2022; Adeleke *et al.*, 2022; Adeleke *et al.*, 2021). These factors have amplified the interests of several researchers on biomass briquetting.

Due to growing demand for sustainable energy, there has been increasing interest in biomass briquettes as alternative fuels. However, the inconsistencies in available experimental design, scarce statistical validation and coupled with fuel properties that are unrealistic are noticeable problems in past studies. Their performance depends on elemental composition (ultimate analysis) and thermal decomposition characteristics (proximate analysis). Understanding these relationships is critical for optimizing fuel quality. Therefore, in attempt to obtain a suitable mixture from biomass residues for briquettes production, the physical properties and combustion characteristics of biomass briquettes need to be studied (Ajimotokan *et al.*, 2019a). By addressing anomalies in earlier experimental designs and offering optimal formulation guidelines for sustainable biomass fuel production, the current work offers a statistically validated assessment of the combined effect of sawdust and coconut coir composition on briquette fuel performance. This study thereby aims at investigating the suitability of the admixture of coconut coir and sawdust particles (agrowastes) using starch gel as a binder to produce briquettes fuel. The objectives were to: determine the proximate composition of the produced fuel, evaluate the statistical differences among the five formulations, and assess the suitability of the fuel as a source of solid fuel.

2. METHODOLOGY

2.1 Materials

The major materials used in this study are agro-residues (coconut coir and sawdust from Africa birch (*Anogiessus leicarp* / Igi ayin), which were sourced within the Ilorin Emirate, Kwara State, Nigeria (8.5°N Latitude and 4.55°E longitude). Cassava starch gel used as a binder for the production of the briquettes samples was obtained from a Cassava processing factory in Gaa-Akanbi, Ilorin, Nigeria (8.4689° N Latitude and 4.5826°E longitude).

The equipment and tools used for processing the materials in the study includes Moisture Analyzer (90g, 115v, 60Hz of 40; 200°C), Furnace (LF3/F4244 Model, Vecstar Ltd, United Kingdom), Hydraulic Compression Machine (DA66T of 125T/4000), Oven (CWL112P4RW5), Digital Weighing Balance (model PBK989-CC150), Micrometer Mesh Sieve (of about 0.5mm), fabricated local grinding Machine, Mold, Mortar and Pestle.

2.2 Methods

2.2.1 Materials preparation

Sample of Coconut coir was cleaned by handpicking the foreign materials from the raw samples, and sun-dried for 240 hours (minimum of 4 hours in a day) to reduce their moisture contents. The dried samples were then grinded using a locally fabricated milling machine at Ipata market in Ilorin, Nigeria. To achieve a consistent uniform texture in the samples, the dried samples were sieved with a set of British Standards (BS) sieves to obtain samples of 0.5 mm sieve size (Odusote *et al.*, 2017). Figure 1 and 2, show the samples of the coconut coir before and after ground undergoing sun drying process. The ground coconut coir was kept in transparent polythene bag to prevent it from mixing with foreign materials.

The 0.5 mm particle size is achieved using a set of standard BS sieves to ensure a consistent, uniform texture for the ground samples.

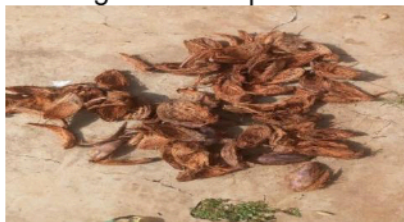


Figure 1: Coconut coir being sun dried

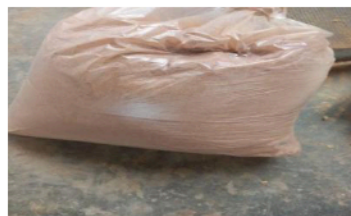


Figure 2: Grinded coconut coir (0.5mm)

The sample of the sawdust from African birch waste (*Igi Ayin*) was obtained at Tanke sawmill, beside NNPC filling station, Ilorin, Nigeria (latitude 7.40° N and longitude 3.91° E) and manually sorted to remove the various forms of dirties and foreign materials such as sand, stone, ashes and plant residues. It was then sun-dried at an average temperature of 33°C for 240 hours (minimum of 4 hrs per day) to reduce the moisture content. The dried sawdust was later grinded with a locally fabricated grinding machine to reduce particle sizes. The grinded sample was sieved with the aid of sieve and sieve shaker to a size of 0.5 mm. The particle size of 0.5 mm is in accordance with the previous work (Kpalo & Zainuddin, 2020; Ogundipe *et al.*, 2021).

2.2.2 Briquette preparation

The briquettes were produced using varying compositions as shown in Table 1 and further analyzed for ultimate analysis (C, H, O), proximate analysis (ash, volatile matter, fixed carbon), higher heating value (HHV) and physical properties (density, moisture, durability).

Cassava starch gel (made from 90% starch power and 10% water) was used as the binder for the production of the briquettes due to its relative availability, low energy consumption and smokeless purposes (Oyelaran *et al.* 2015; Tembe *et al.*, 2014). Table 1 shows the mixing ratios of the samples used for the production of the bio-briquettes.

The briquettes were produced using Hydraulic Compaction Machine (DA66T of 125T/4000) under controlled pressure and temperature. The process employed a binder and high-pressure briquetting method (Ajimitokan, 2019a). Each ratio of the mixed composition of coconut coir, sawdust and starch binder were fed into the mold and put under an applied pressure of about 5 Mpa at a dwelling time of 5 minutes to allow for the homogenous mixture of bio-residues in the mould in preventing spring-back effect (Ajimitokan, 2019a). Each of the briquettes formed from the mold were transferred to a furnace (LF3/F4244Model, Vecstar Ltd, United Kingdom) where the briquette is heated to a curing temperature of 105 °C for 1 hour to remove moisture. The samples were kept under sealed polythene bags for characterization. Both the ground samples of coconut coir and sawdust were thoroughly mixed in five different ratios the ratio varying from 100g of coir to 0 g of sawdust for sample A to 50g of coconut coir to 50g of sawdust for sample E with all the ratios having 5g of starch added as binder. The selection of binder weight is based on previous studies with binder concentrations between 4 -20 wt% (Nganko *et al.*, 2024; Van der Westhuizen *et al.*, 2024; Lavanya, 2026; Pratinthong *et al.*, 2025) which provided maximum mechanical strength and combustion efficiency.

Table 1: The mixing ratio for the production of different briquette samples

Sample code	Coconut coir (wt%)	Sawdust (wt%)	Starch (wt%)
A	100	0	5
B	80	20	5
C	70	30	5
D	60	40	5
E	50	50	5

2.2.3 Characterization of the briquette samples

The effectiveness and efficiency of the produced briquette samples were determined by examining the moisture content, ash content, volatile matter, fixed carbon, elemental composition, heating value, density, relaxed density and durability (Saeed *et al.*, 2021). These involved proximate and ultimate analysis, which is fundamental and necessary as starting point for characterization of any solid biofuel (Racero-Galaraga *et al.*, 2024).

2.2.4 Ultimate analysis

The briquettes' elemental compositions [such as carbon (C), hydrogen (H), and oxygen (O₂)] were estimated using equations 1, 2, and 3, respectively as adopted by Ajimotokan *et al.* (2019a), which were evaluated at an estimate of 95% confidence level. These values were evaluated in triplicate and the final composition presented as the average:

$$C = 0.637 F_c + 0.455 V_m \quad (1)$$

$$H = 0.052 F_c + 0.062 V_m \quad (2)$$

$$O = 0.304 F_c + 0.476 V_m \quad (3)$$

Where F_c represents percentage fixed carbon (weight %), V_m represents volatile matter (weight %)

2.2.5 Proximate analysis

2.2.5.1 Moisture content

The sample water content (Moisture content) was determined by using ASTM E871 method as a guide. The briquette samples of known weight were oven-dried (LF3/F4244Model, Vecstar Ltd, United Kingdom) by which determination of moisture content of briquettes, that is the water content of the samples, was dried at a specific temperature of about $110 \pm 5^\circ\text{C}$ for 1 hour. The sample's moisture content was then calculated using relationship in equation 4 (Ajimotokan *et al.*, 2019a; Inegbedion, 2022).

$$\text{Moisture content} = \frac{\text{Initial weight sample} - \text{Oven dried weight sample}}{\text{Oven dried weight sample}} \times 100\% \quad (4)$$

2.2.5.2 Ash content

The ash content of the samples was determined using ASTM E1755 standard. One gram of each pulverized briquette sample was measured and then placed in a crucible of known mass and oven-dried to constant mass. These samples were heated in the furnace (LF3/F4244Model, Vecstar Ltd, United Kingdom) at a temperature of 550°C for five hours and weighed after cooling in a desiccator. The ash content was then estimated from the percentage loss in mass of the sample using the expression in Equation 5 (Ajimotokan *et al.*, 2019b).

$$\text{Ash content} = \frac{w_3 - w_1}{w_2} \quad (5)$$

Where w_1 = initial weight of the empty crucible, w_2 = sample weight and w_3 = final weight of the sample and crucible.

2.2.5.3 Volatile matter

The volatile matter was determined using ASTM E872 standard as a guide. One gram of each pulverized briquette samples was measured and placed in a crucible of known mass. It was then oven-dried to a constant mass. After, the samples were heated in the furnace (LF3/F4244Model, Vecstar Ltd, United Kingdom) at a temperature of 950°C for 7 minutes and weighed after cooling. The volatile matter (V_m) was then evaluated as the percentage loss in mass of the sample using equation 6 (Dewi *et al.*, 2023; Inegbedion, 2022)

$$V_m (\text{wt}\%) = \frac{B - C}{C} \times 100\% \quad (6)$$

Where B is the weight of the oven-dried sample and C is the weight of the furnace-dried sample.

2.2.5.4 Fixed carbon

The percentage fixed carbon of each sample of briquette was estimated using the relation in equation 7 (Ajimotokan *et al.*, 2019b; Inegbedion, 2022).

$$F_c (\text{wt}\%) = 100 - (V_m + M_c + A_c) \quad (7)$$

Where F_c is the (wt%) fixed carbon obtained for each briquette sample, V_m is the (wt%) volatile matter obtained for each briquette sample, M_c is the moisture obtain for each briquette sample and A_c is the (wt%) ash content obtain for each briquette sample.

2.2.6 Determination of shatter index

The durability of the briquette was examined by the shatter index. The briquette samples were dropped repeatedly from a height of 1.5 m onto the solid base. The fraction of the briquette that was retained was

used as index of briquette failure; The shatter index was determined by the equations (8) and (9) (Oriabure *et al.* 2017; Aliyu *et al.*, 2021)

$$\text{Percentage weight loss} = \frac{\text{Initial weight} - \text{final weight after shatter}}{\text{Initial weight}} \times 100 \quad (8)$$

$$\text{Shatter index} = 100 - \text{percentage weight loss} \quad (9)$$

2.2.7 Estimation of higher heating value

The Higher Heating Value (HHV) of each sample of the briquette was estimated using the empirical correlation which is based on proximate analysis parameters (Parikh, *et al.*, 2005). This method is widely accepted for predicting energy content especially because of nonavailability of bomb calorimeter measurement. The correlation is as presented in equation 10.

$$\text{HHV (MJ/kg)} = 0.3536F_c + 0.1559V_m - 0.0078A_c \quad (10)$$

2.6 Statistical Analysis

The mean was evaluated using equation (11)

$$\bar{x} = \frac{\sum x_i}{n} \quad (11)$$

Where $\bar{x}$ is the mean, x_i is the individual values and n is the number of observations?

The Standard Deviation (SD) is determined from equation (12)

$$SD = \sqrt{\frac{\sum (x_i - \bar{x})^2}{n-1}} \quad (12)$$

The sample sizes are all in triplicates ($n=3$) and the results presented are expressed as mean $\pm$ SD. Statistical analysis were executed with SPSS Statistics (version 23.0, IBM Corp., Armonk, NY, USA). The statistical analysis was conducted between groups using Analysis of Variance (one-way ANOVA). The decision rule imposed was if $p < 0.05$, there is significant difference between the concern groups. However, if the P value obtained is greater than 0.05, then there is no significant difference between the groups.

3.0 RESULTS AND DISCUSSION

3.1 Elemental Composition of the Fuel Sample

The average elemental compositions of the briquette samples produced are presented in Figure 3, with the carbon content ranging from 41.67–43.27 wt.%, while hydrogen ranged from 5.25–5.40 wt.%. The results revealed that Sample E recorded the highest carbon (wt%) content (43.27%), while sample A had the lowest carbon (wt%) content (41.67%). The hydrogen wt% content in the briquettes in sample A is 5.25 %, sample B (5.37%), sample C (5.32%) sample D (5.36%) and sample E is 5.40%. Meanwhile, the oxygen wt% in the briquette samples decreases in the order of sample E (40.17 %), sample B (40.10 %), sample D (39.82 %), sample C (39.70%) and lastly sample A (39.17%).

Studies have shown that the elemental compositions of solid fuel affect its energy content and fuel ratio (Racero-Galaraga *et al.*, 2024; Ajimotokan *et al.*, 2019a; Lan *et al.*, 2017). The percentage by weight (%wt) of carbon (C) and hydrogen (H) in bio-briquettes obtained strongly influence the fuel (bio-briquette) quality, combustion behaviour, and environmental performance. The higher the %wt of Carbon in a bio-briquette, the higher the heating value (HHV), and the better fuel efficiency, and its overall quality (Geberehiet *et al.*, 2026; Akam *et al.*, 2024; Fajobi, 2022; Ezenwa *et al.*, 2024; Castro-Díaz *et al.*, 2024, 2019; Demirbaş, 2004; Jenkins *et al.*, 1998). The Carbon content is also known to be the dominant contributor to energy release during combustion (Picheau *et al.*, 2022).

The increase in percentage content of sawdust in the fuel briquettes' components resulted into the increase in the carbon content of the briquettes. This can be attributed to the percentage of carbon content

in the sawdust, because of its highly concentrated lignocellulosic biomass (cellulose, hemicellulose, and lignin) (Manyuchi *et al.*, 2018).

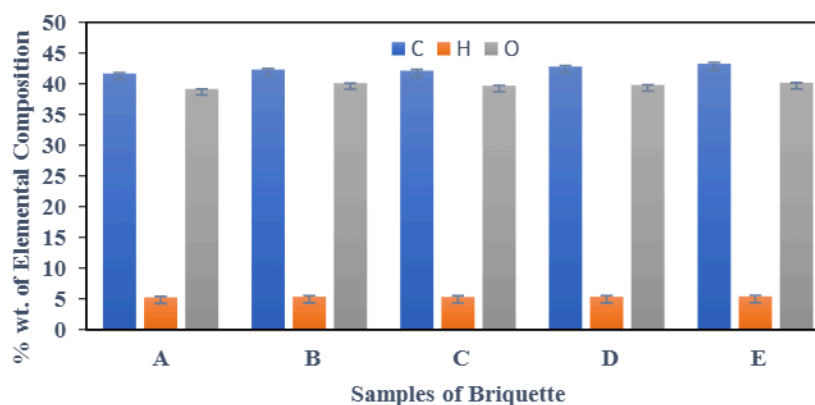


Figure 3: Elemental composition of Briquette Samples in Different Mixing Ratios of coconut coir and Sawdust.

Meanwhile, the Hydrogen content in the briquettes varies with sample E having the highest value (5.41%), followed by sample B (5.37%), sample D (5.36%), sample C (5.32%) and lastly sample A (5.25%). In bio-briquette fuel, high carbon and hydrogen content significantly improved HHV (Ajimotokan *et al.*, 2019; Saeed, 2021). Combination of high carbon and moderate hydrogen in briquette leads to high energy output (calorific value), stable combustion and acceptable ignition that are required by a good briquette.

The results (Figure 3) revealed that oxygen exhibited a fluctuating but generally high trend (39.17 – 40.17%wt). High oxygen content tends to lower the calorific value of the fuel while high carbon content tends to form high-grade biomass fuel (Ismaila *et al.*, 2013).

3.2 Combustible Properties of the Fuel Samples

The result of proximate analysis showing the combustible properties of the briquettes are presented in Table 2. From Table 2, the results of the ash content, volatile matter, percentage fixed carbon and HHV of the biomass briquettes are in the ranges of 3.0 – 6.0%, 74.5 – 76.9%, 11.51 – 14.07% and 15.88 – 16.71 MJ/kg respectively. The relatively low standard deviation in values presented points towards good measurement reliability and experimental repeatability.

Table 2. Proximate Analysis and Higher Heating Value (Mean±SD, n=3)

Samples	Ash Content (%) (Mean±SD)	Volatile Matter (%) (Mean±SD)	Fixed Carbon (%) (Mean±SD)	HHV (MJ/kg) (Mean±SD)
A	6.0±0.069	74.5±0.265	12.2±0.100	15.88±0.020
B	4.5±0.069	76.9±0.361	11.51±0.017	16.02±0.120
C	5.0±0.076	75.7±0.361	12.07±0.059	16.03±0.075
D	4.0±0.053	74.9±0.300	13.71±0.095	16.49±0.095
E	3.0±0.069	75.4±0.346	14.07±0.015	16.71±0.195

For the ash content, the result obtained from this study (3 - 6%) is in agreement with the result of the study (4.43-4.65%) by Alias *et al.*, (2025), but different from what was obtained by Muborok *et al.*, (2026) which was within a range of 14.95 - 23.62%. Sample E recorded the lowest value while sample A exhibited

the highest value. Sample A and sample B recorded the lowest and highest volatile matter, while sample A and sample E has the lowest and highest HHV, respectively. The samples C and E respectively had the lowest and highest percentage fixed carbon. The carbon and hydrogen contents influence the heating value directly (Waheed et al., 2022).

The proximate analysis results show that the briquettes developed are endowed with promising combustion characteristics which is suitable for energy applications. The result shows moisture contents with values below 10 % suggesting good storage stability and improved ignition efficiency (Pari et al.2023). High level of moisture contents denotes reduce combustion temperature and increased smoke emission. This is similar to the result obtained by Abdel Aai, (2023) which was 8 % moisture contents while working with briquette made from pruning residuals of *Ficus nitida* trees.

The ash content ranged from 3 to 6% which is within the generally acceptable limits for biomass fuels which was also buttress by findings from similar work done by Dewi, (2019). Lower ash content improves operational efficiency as a result of reduced fouling and slagging in the combustion system. A higher ash content points towards higher mineral composition in the raw material used for the briquette and gives a lower heating value (Smolka-Danielowska & Jabłońska, 2022; Saeed, 2021).

The values of the volatile matter obtained from this study which is between 74.5 to 76.9% indicate both good ignition property and rapid flame propagation property. This range of values are also in the same range of values obtained by Noah *et al.*, (2019). They obtained volatile matter values of 84.83% in their study. However, other researchers like Dewi *et al.*, (2023) obtained 43.19% as the value of volatile matter which was lower than the current work. High level of volatile matter content improves combustion reactivity and increases flame stability during burning (Zhang *et al.*, 2025). These are desired in good fuels for household and industrial applications.

The fixed carbon content ranged from a value of 11.51 to 14.07%. This is similar to the range of values reported by Ronoh *et al.*, (2025) while working on briquette made from sawdust, coffee husk and maize stalk. This is also within the acceptable values 10 to 30% reported in literature (Weber & Quicker, 2018). The value reported in this study indicate moderate char formation and sustained combustion duration. The higher values of fixed carbon in samples D and E points towards longer burning time and improved energy output.

The HHV of the briquettes ranged from 15.88 to 16.71 MJ/kg which is within the range of values obtained by Lavanya, (2026) and also Muhammed & Lawal, (2025). These are analogous to typical values of biomass fuels such as found in woods and other agricultural residues. These values from the correlation falls within the typical range of 15 to 20 MJ/kg for lignocellulosic biomass fuels (Huang & Lo, 2020). Thus, the agreement with values in literature affirms the reliability of the correlation used in the absence of direct calorimeter measurement. Sample E demonstrated the highest HHV (16.71 MJ/kg) due to its high carbon (43.27 wt.%) and low ash (3%) is an indication of increased combustible material availability. The higher the carbon content, the higher the calorific value (HHV). This characteristic that allows release of more energy during combustion is being exhibited by the briquette, especially sample E. It implies that Sample E that possessed the higher carbon content has the higher energy density and better fuel efficiency (Ngene *et al.*, 2024; Gimba *et al.*, 2022; Ibitoye *et al.*, 2022; Ajimotokan *et al.*, 2019). The results of the moisture, ash, volatile matter and percentage fixed carbon of the biomass briquettes revealed that the fuels may be suitable for use as fuels in domestic and industrial applications. This was buttressed by Lavanya, (2026), that any briquettes with HHV of 15.3 MJ/kg and above has met industrial standard and suitable for industrial applications.

Sample E (43.27% C, 5.40% H, low ash, 3%) showed the best energy performance and sample A recorded the lowest performance being sample with high ash and lowest carbon. Sample E had the highest carbon and hydrogen content. The Increased carbon corresponded with increased HHV, which confirms that carbon is the primary contributor to fuel energy.

The ash content and volatile matter in bio-briquettes are critical parameters from proximate analysis, and they directly control combustion efficiency, ignition, emissions, and energy output. The typical desirable ranges of Ash content required in a good briquette to ensure good ignition and high calorific value are < 5 - 10% (Nikiforov *et al.*, 2023), while the typical required range of hydrogen in briquettes is 5–8 wt% (Geberehiet, *et al.*, 2026).

Higher ash content in a bio-briquette implies less combustible material and lower heating value (HHV) in the fuel (Sheng & Azevedo, 2005). Low ash content correlates with higher calorific value, indicating better fuel quality (Falemara *et al.*, 2018). The energy efficiency of bio-briquette reduces with high ash content, since ash acts as an inert material in the fuel. The combustion efficiency is reduced by slowing down the heat transfer. The briquette is harder to ignite, sustain combustion and more unburnt residue with high ash content in the briquette (Ifa *et al.*, 2020). Ash increases combustion remnants, thereby lowering heating effectiveness (Falemara, *et al.*, 2018).

High volatile matter in bio-briquette makes ignition easier and smoother, and support rapid flame formation with long flames, while low volatile matter enhances steady heat output and glowing combustion (Onuegbu *et al.*, 2021; Ifa *et al.*, 2020; Falemara, *et al.*, 2018).

3.3 Physical Properties of the Briquettes

The physical properties of the briquettes analyzed in this research are factors of briquettes density, relaxed density, moisture content and shatter index or durability. The values for physical properties of the samples produced are presented in Table 4.

The briquettes density ranged from 0.91–1.09 g/cm³, while the moisture content ranged from 6.87–7.77 %. The higher density improved interparticle bonding and also increases porosity which leads to heat transfer efficiency and combustion stability (Wu *et al.*, 2025; Smith *et al.*, 2021; Muazu & Stegemann, 2015; Saika & Baruah, 2013). All samples had moisture contents (7.09 – 7.53%) which are within the acceptable values, because the values are less than 10 %, indicating good storage stability (Agriculture and Horticulture Development Board, 2026). Low moisture content is essential because to enhance ignition, improve combustion efficiency and prevents energy loss during drying (Kaliyan & Morey, 2009).

Table 4: shows the physical properties of the briquettes produced

Samples	Density (g/cm ³)	Relaxed density (g/cm ³)	Shatter index (%)	Moisture content (%)
A	0.91 ± 0.027	0.098 ± 0.003	0.9962 ± 0.050	7.77 ± 0.046
B	1.07 ± 0.032	0.385 ± 0.012	0.7134 ± 0.036	7.08 ± 0.06
C	1.03 ± 0.031	0.38 ± 0.011	0.9755 ± 0.049	7.09 ± 0.046
D	1.04 ± 0.031	0.384 ± 0.012	0.9363 ± 0.047	6.87 ± 0.069
E	1.09 ± 0.033	0.39 ± 0.012	0.9562 ± 0.048	7.43 ± 0.040

The shatter index which measures the percentage of material required to break down the briquette into smaller particles when subjected to stress is significant in determining the durability and structural integrity of the briquettes (Aliyu *et al.*, 2022; Tarka *et al.*, 2023; Orisaleye *et al.*, 2024). The index is a crucial parameter considered in handling or transportation of the briquette. The results in Table 4 show the shatter index values to be in the range of 0.7134% for sample B to 0.9962% for sample A. An indication that sample A exhibited the best structural integrity and resistance to breaking out of all the briquette samples. While sample B may be more prone to fragmentation under stress due to its lowest value of shatter index. A higher shatter index is often associated with higher compressive strength, which can be advantageous in applications where durability is essential (Bhatia *et al.*, 2020).

The combustion characteristics, energy density, and overall effectiveness of bio-briquette as a fuel source are affected by the moisture content, thus make it a critical factor that has influence on the performance and efficiency of briquettes (Bhatia *et al.*, 2020). The percentage moisture contents for the briquette samples are varies from 7.09% in sample B to 7.53% in sample E as shown in in the results presented in Table 4.

Sample B with 7.09 % moisture content is likely to perform better in terms of energy release compared to Sample E with moisture content value of 7.53%. Lower moisture content enhances combustion efficiency and energy output in general (Kumar *et al.*, 2019, Lal *et al.*, 2025; Oyebamiji *et al.*, 2025). High moisture content can lead to incomplete combustion, resulting in lower heat output and increased emissions (Kumar *et al.*, 2019; Lal *et al.*, 2025; Oyebamiji *et al.*, 2025, Ayaa *et al.*, 2025).

Relaxed density is an important metric that reflects the density of the briquettes after they have been compacted and allowed to expand slightly. For understanding the briquettes' handling and storage characteristics information on relaxed density is important. The relaxed density for the samples ranges from 0.098 g/cm³ in sample A to 0.390 g/cm³ in sample E. With the highest value (0.390 g/cm³) of the relaxed density exhibited by sample E is an indication that the sample has a more compact and possibly more energy-dense briquette, which may provide better performance during combustion. While sample A with the lowest relaxed density (0.098 g/cm³) is the less dense sample and likely to be potentially less efficient in terms of energy output (Smith *et al.*, 2021).

In summary, the superior performance of Sample E is attributed to its high carbon and hydrogen, low ash content, and high density.

3.4 Statistical Analysis

Statistical analysis of variance (ANOVA) was performed on the samples. This was done for ash content, fixed carbon, moisture content, volatile matter and HHV. For fixed carbon, result of the ANOVA test showed that there is a high significant difference in fixed carbon content among the five samples of A, B, C, D, and E ($F=410$, $p < 0.0001$). To identify which sample pair differs, we apply Tukey's (HSD) post Hoc test. Result of the Tukey's test shows that B differs from A, B, C, D and E. A and C are similar but different from B, D, E. D and E are similar but different from B, C and A. D and E are significantly different from each other.

ANOVA was done on the ash content of the samples. Result revealed that there was very high significant difference among group of five samples ($F=817.58$, $p < 0.0001$). The result shows that each of the samples has an exclusively different ash content which is significantly different from all others.

The statistical analysis performed on the samples revealed that there was significant difference in volatile matter among the five samples ($F=23.39$, $p < 0.0001$). Tukey HSD post-hoc test revealed that A and D are similar, D, E, and C are similar; B is higher than everyone and A and E are different.

For moisture content, the Analysis of Variance revealed that there is a significant difference between groups of samples ($F=28.89$, $p < 0.0001$). Application of Tukey HSD test on the moisture content gave a result of $HSD = 0.143$. This implies that any difference between pairs of samples with mean value differing by more than 0.143 means there is significant difference between such samples. Thus, B differs from A, D, E and E differs from B, C, and A

One-way ANOVA done on HHV revealed that there is significant difference between the samples ($F=27.47$, $p < 0.0001$). For Tukey's HSD test on HHV of the samples, it gave HSD of approximately 0.312. Which implies that for any difference between means of samples that is greater than 0.312, there is a significant difference between the samples. D is significantly different from A, B, C; and E is significantly different from A, B, and C but similar to D.

3.5 Limitations of the Study

The HHV (calorific value) presented in this study was estimated from empirical correlation instead of measurements from bomb calorimeter. For future work, experimental methods should be employed in evaluating the HHV and long-term combustion performance should be assessed in real heating system.

4.0 CONCLUSIONS

This study evaluated the influence of ultimate and proximate properties on the performance of bio-briquettes. The following conclusions are made from the results and discussion of this study:

1. Increased carbon and hydrogen content significantly improved Higher Heating Value (HHV). Sample E with 43.27% Carbon and 5.4% Hydrogen showed the best energy performance.
2. High volatile matter enhanced ignition and flame intensity.
3. Ash content negatively impacts the fuel quality by reducing the fuel combustion efficiency and calorific value, while the Volatile matter enhances ignition and flame intensity
4. Higher density improved energy per unit volume. Meanwhile, all samples percentage moisture contents are within the acceptable moisture content (<10 %), indicating good storage stability.
5. Sample A with 6% ash content had the lowest Higher Heating Value (HHV), while Sample D with 5.79 % Fixed Carbon demonstrated superior combustion stability and longer burning time.
6. Fixed carbon improves combustion duration
7. High level of volatile matter exhibited by sample E may lead to rapid combustion and emissions
8. Sample E with 14.07% Fixed Carbon demonstrated superior combustion stability and longer burning time.
9. Based on the results of having the highest HHV (16.71 MJ/kg), lowest ash content (3%) and highest density (1.09 g/cm³), sample E is the most appropriate briquette for selection for maximum energy values.

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