ASEAN Journal for Science and Engineering in Materials

Journal homepage: https://ejournal.bumipublikasinusantara.id/index.php/ajsem

Production and Characterization of Briquettes from Agricultural Wastes for Sustainable Energy Solutions

Ahmed Umar [1], Abdulrahman Abdulmumin Gbenga[1,], Muhammad-Najeeb Oluwafemi Yusuf [2], Abdulrasheed Faridah[1], Adeyemo Tijesunimi Emmanuel[1], Ajuwon Fadhilat Adekitan[1]*

[1]University of Abuja, Gwagwalada, Nigeria

[2]National Agency for Science and Engineering Infrastructure (NASENI), Nigeria

*Correspondence: E-mail: abdulmumin.abdulrahman@uniabuja.edu.ng

ABSTRACT

The study evaluates the potential of rice husk (RH) and sawdust (SD) as energy sources by analyzing their physicochemical properties and combustion efficiencies. These common waste materials from Gwagwalada, Abuja, Nigeria, were processed into briquettes at varying ratios. Proximate analysis showed moisture content of 7.5–9.2% and ash content of 2.1–3.5%. Calorific values ranged from 18,509.84 kJ/kg (100% SD) to 22,658.77 kJ/kg (100% RH). The burning rate (BR) correlated with calorific value, with the 50:50 SD/RH mixture having the highest BR (0.003 g/min), indicating rapid combustion, while 100% SD had the lowest BR (0.0015 g/min), supporting slower combustion. All briquettes exhibited smokeless behavior, reducing greenhouse gas emissions and offering a clean energy alternative. This study highlights the potential of agricultural waste for energy security, environmental management, and rural economic development in Nigeria.

ARTICLE INFO

Article History:
Submitted/Received 20 Dec 2024
First Revised 18 Jan 2025
Accepted 20 Mar 2025
First Available online 21 Mar 2025
Publication Date 01 Sep 2025

Keyword:
Briquette,
Burning rate,
Calorific value,
Energy sustainability,
Rice husk,
Sawdust.

1. INTRODUCTION

Energy input currently required to drive the world's multisectoral economy in the fourth industrial revolution era is believed to undermine its sustainability in both developing and underdeveloped nations due to an exponential increase in energy demand and consumption (Ahmad & Zhang, 2020; Miao *et al*., 2022). Nigeria, like many developing nations in the sub-Sahara, heavily relies on fuels derived from fossilized sources, to close energy gaps required to stimulate socio-economic growth (Oloyede *et al*., 2023). Past studies have made significant progress in the conversion of specific biomass that can be processed into suitable forms of energy fuels, with such biomass including but not limited to twigs (Niambe *et al*., 2024), firewood (Alabi *et al*., 2024), and charcoal (Łaska & Ige, 2023). However, fewer concerns have been raised regarding the sustainability of these biomass either due to their availability or how they have adversely impacted the climate as a result of significant greenhouse gas (GHG) emissions. Consequently, it has necessitated a global search for alternative, more accessible, sustainable, and environmentally friendly energy resources (Wang & Azam, 2024). Hence, the processing of biomass from agricultural wastes has emerged as a promising and potent solution to the aforementioned issues (Adewumi *et al*., 2024; Banerjee, 2023)

There is growing interest in finding alternative sources to fossil fuels, in a bid to achieve environmental sustainability and economic reliability, and studies have revealed that biomass is a dependable source among several renewable energy resources, due to its ubiquitousness (Giwa *et al*., 2017; Wang & Tester, 2023). They serve as excellent starting materials for bioenergy production, as their diverse array of resources from crop residues (corn stover, rice husk), wood shavings (sawdust), etc. are readily available and can be easily processed. Reports have also established that the use of wood fuel as an energy source in Nigeria accounts for about 60 % of Nigeria's total energy consumption, and it is used for domestic activities in both rural and urban households (Ali *et al*., 2023; Łaska *et al*., 2023; Maina *et al*., 2020). Charcoal, in particular, is a preferred heating material due to its general affordability, even as it impedes forest conservation (Łaska *et al*., 2023).

Firewood, twigs, and charcoal biomass are reported to be the major feedstocks for renewable energy production in most developing countries found in Sub-Saharan Africa (Alabi *et al*., 2024; Niambe *et al*., 2024). In highly dense regions of Nigeria, such as the arid north, fuel wood remains the predominant energy resource for both rural and urban communities, and is used for cooking and other domestic activities, thus, making up a significant percentage of their total energy stock (Ali *et al.*, 2023). States found in the savannah vegetation belt also account for large-scale production of charcoal and have contributed to the depletion of approximately 1607.16 hectares of savanna woodland area annually, with 64.3 % occurring around forest reserves. An estimated 133.93 hectares are lost monthly to deforestation, with about 65 % occurring in surrounding forest woodlands (Ekpo & Mba, 2020). Quite a few studies have reported similar cases across other vegetational zones (Agunloye *et al.*, 2020; Chomini *et al.*, 2022). This huge dependence on biomass is also evident in the trend of energy consumption by fuel type over the years, which shows a great dependence on fuelwood for various energy needs (Obi *et al.*, 2023).

Nigeria's rice cultivation has increased exponentially over the past decades, as the country's annual production stands at around 5.2 million metric tons of milled rice. However, much of the volume of residues obtained from this crop is largely underutilized (Odejobi *et al.*, 2024; Okey, 2023). The husk, being a main by-product obtained from the rice milling process accounts for up to 200 kg per ton of rice paddy (Tayeh *et al.*, 2021), and can be used for several purposes such as additive in clay processing (cite), soil remediation (cite), animal

p-ISSN: 2828-920X e-ISSN: 2828-9951

feed supplement and feedstock for biomass fuel production (Akhter *et al.*, 2021; Ríos-Badrán *et al.*, 2020). Therefore, full utilization of this waste material offers a sustainable alternative that can help reduce its waste volume (Ullah *et al.*, 2021). Similarly, sawdust obtained from mills is often disposed of indiscriminately, which further exacerbates health risks due to particulate transboundary dispersions in the atmosphere (cite). The utilization of this resource through conversion into briquettes can also offer greater economic and environmental benefits (Akolgo *et al.*, 2021).

Even though most agricultural residues with potential for energy use are obtained perennially, seasonal variability can also affect their abundance throughout the year, especially during harvest seasons in agrarian areas of Nigeria (cite). Annually, seven million tonnes of residues are generated from cultivated crops, (Ayodele & Olubunmi, 2017). Most farmers opt to burn these residues during the post-harvest period via a process called stubble burning. Such a process is accompanied by the release of harmful pollutants into the atmosphere that consequently compromise air quality and cause climate change. (Abdurrahman *et al.*, 2020; Singh, 2024). This sharp practice is also reported to deplete soil nutrients that may lead to reduced agricultural yields through soil degradation (Pradhan *et al.*, 2024). The lack of affordable and accessible technologies, to convert these residues into useful products leaves farmers with limited options and, thus, may be detrimental to the environment, and impact the livelihood of farmers (Rahimi *et al.*, 2022). Harnessing these waste materials into biofuels will extensively contribute to greater benefits via adequate resource management.

The physicochemical profiles of some biomass such as moisture content (Ivanova *et al.*, 2012), net heating value (NHV) (Maxwell *et al.*, 2019), and burning rates necessary to undergo efficient (Hroncová *et al.*, 2016; Jiang *et al.*, 2024) combustion have been extensively studied. Hence, studies have revealed that briquette technology proffers effective solutions to issues related to efficient combustion by pelletization of biomass into briquettes. In addition, it has been found to improve the calorific value of the products formed (Bot *et al.*, 2024; Marreiro *et al.*, 2021; Yunusa *et al.*, 2023). Residues derived from purpose-grown crops such as rice husk, corn hub, palm kernel shells, cotton stalk, sawdust, cocoa pod, coconut husk/pod, and groundnut husk are widely reported to have high calorific values (cite), hence, they serve as alternative fuel sources for domestic applications, especially in cooking by rural dwellers (Hamzat *et al.*, 2019; Japhet *et al.*, 2020).

Despite the prospects found in the conversion of biomass to briquette, which is a valuable energy resource, it is still not fully utilized in many developing countries as a result of technological limitations and socio-economic factors (Elehinafe & Okedere, 2023; Marreiro *et al.*, 2021). There is a need to investigate the combustion characteristics of residues derived from specific biomass such as rice husks and sawdusts, to make their utilization more practical and efficient. Hence, this study aims to utilize two agricultural residues for making briquettes, to provide affordable and sustainable alternative fuel for households and industries in Nigeria. In addition, there have been concerns about elusive threats to food security relating to the utilization of crops for briquetting, hence, the need to focus on substrates derived from cassava residues as a suitable binder.

2. METHODS

2.1. Materials

Samples of sawdust and rice husk were collected from a local sawmill and rice mill, respectively. The cassava starch was obtained from the central market, all within the metropolitan area of Gwagwalada, in the Federal Capital Territory of Nigeria. Gwagwalada town lies on Latitude 8°56'42.89"N and Longitude 7°4'55.57"E with daily average temperature ranges of 25 ℃ and 35 ℃ (Worldweather,2024). The climate is equatorial with distinct wet and dry periods; with wet and dry periods occurring between April – September and October – March, respectively. The samples were washed with distilled water, then dried under ambient conditions (27 ℃), and kept safe inside a polythene bag for further use. The sample of sawdust and rice husk are presented in **Figures 1 (a)** and **(b)**.

Figure 1. Material used: (a) sample of sawdust, (b) Sample of rice husk.

2.2. Methods
2.2.1. Sample treatment

Samples of rice husk (RH) and saw dust (SD) were soaked inside separate plastic containers filled with distilled water at room temperature for 3 days until partial biodegradation was observed. Both soaked samples were drained, leaving residual pulpy substances. They were thereafter pulverized. The samples were thereafter carbonized for 1 h at 400 °C in an oxygen-free environment, to obtain a constant weight. They were further collected separately and stored for subsequent use.

2.2.2. Preparation on starch gel

1 L of water was poured inside a pot and brought to a boiling point. 200 g of cassava starch was mixed with cold water (0.5 L) inside a separate container to form a suspension, which made it easier to gel in hot water. Once the water boiled, the paste was poured into the boiling water and continuously stirred for approximately 15-20 minutes until it became colloidal. The starch solution was allowed to cool to room temperature for 2-3 hrs. before use.

2.2.3. Briquettes preparation from composites

The carbonized rice husk (RH) and sawdust (SD) samples were thoroughly mixed and sieved to attain a uniform size of 0.6 mm. The mixture was thereafter optimized by varying the ratio of their masses to produce five different sample mixtures The prepared cassava starch was used as a binding agent to compact each sample mixture with the aid of a manually operated screw press machine under a pressure of 10 MPa. The compacted products were produced in ratios as described in **Table 1**. The products were thereafter oven-dried at 40 °C for 3 hrs. to achieve a constant weight before characterization was carried out (**Figure 3**).

Table 1. Mixing ratio (%) of briquette feedstock.

Sample	Sawdust (% SD)	Rice Husk (% RH)
A	100	0
B	75	25
C	50	50
D	25	75
E	0	100

The mixing ratio optimization model was used to establish the calorific values and the proximate composition of the pellets produced, and the responses were compared with the characteristics of briquettes reported in similar studies. This was needed to identify major components of the pellet; and to assess the overall eco-friendliness of each product.

2.3. Characterization of Briquettes

2.3.1. Moisture content (MC)

Twenty (20) grams of the sample were weighed into a crucible with the initial and final weights of the crucible were determined on a digital weighing balance. The sample was oven-dried at 105˚C for 24 h. The sample was cooled and reweighed, and the process was repeated till a constant weight was obtained. The percentage moisture content calculated is shown in Equation (1), (2), and (3) (Ofori, 2020).

$$(A + B) - A = B \quad (1)$$

$$(A + B) - (A + C) = B - C = D \quad (2)$$

$$\% \text{ Moisture} = \frac{D}{B} \times 100 \quad (3)$$

Where A is the crucible weight, B is the sample weight, C is the dry sample weight, and D is the moisture weight.

2.3.2. Ash content

The ash content was determined according to ASTM E1755-01 by weighing 5 grams of the sample mixture into a porcelain crucible. The sample was put inside a furnace for 4 h at 550 ˚C. The sample was removed from the furnace and allowed to cool below 200 ˚C for 20 min. The ash was placed inside a desiccator to cool and weigh. The mass of ash content is calculated according to Equation 4 as described by Jume *et al.* (2024).

$$\% \text{ Ash} = \frac{W_3 - W_2}{W_2 - W_1} \times 100 \quad (4)$$

Where W_1 is the previous weight of empty crucible; W_2 is the crucible weight and sample before incineration; and W_3 is the crucible weight and sample after incineration.

2.3.3. Volatile matter

The volatile matter was determined according to the International Organization for Standards 562/1974. 2 g of the pulverized sample was weighed and recorded. The ground sample was carbonized inside a crucible for 5 minutes at a temperature of 800 ˚C and allowed to cool inside a desiccator. The sample weight after cooling was also recorded. Equation 5 was used to calculate the volatile matter content as described by Ofori (2020) For all five samples.

$$\% \text{Volatile Matter Content} = \frac{A - B}{A} \times 100 \quad (5)$$

Where A is the initial weight; and B is the final weight.

2.3.4. Fixed carbon

Fixed carbon content was determined by adding the percentage of moisture content, percentage of ash content, and percentage of volatile matter and deducted from 100, to get the percentage fixed carbon content of each sample. Equation (6) shows the percentage of fixed carbon content as described by Ofori (2020).

% Fixed carbon = 100 – (moisture content + volatile matter + Ash content) (6)

2.3.5. Calorific value

The equation utilized to determine the calorific value (CV, in kJ/kg) using the data obtained from laboratory analysis is described in Equation 7.

$$\mathrm{CV} = \frac{E\Delta T - \Phi - \mathrm{V}}{\mathrm{g}} \tag{7}$$

Where V is the volume of alkali in the calorimeter (kJ), E is the energy equivalent of the calorimeter (≅ 13,039.308 kJ/°C), Φ is equal to 2.3 × length of burnt wire (kJ), ΔT is the change in temperature (°C) and g is the mass of sample (kg).

2.3.4. Determination of burning of rate

The fuel burning rate was determined using the method by other researchers Mohammed and Olugbade (2015). The insulator, Bunsen burner, tripod stand, and wire gauze were arranged on the balance, and their weights were recorded. A briquette sample of known mass was placed on wire gauze and the burner was ignited. This was positioned on top of a mass balance, where the burning rate of the briquette was monitored every 10 seconds until the briquette was completely burnt and constant weight was obtained. The weight loss at time *T* is given by Equation (8).

$$\mathrm{B_R} = \frac{A - B}{\mathrm{t}} \tag{7}$$

Where B_R is the burning rate, g/min; *A* is the initial weight of fuel before cooking (g); *B* is the final weight of fuel after cooking (g); and *t* is the total burning time (min).

Figure 2 shows the process flow chart of the briquettes produced by the variation of rice husk and saw dust mixtures.

3. RESULTS AND DISCUSSION

Figure 3 presents the briquettes produced from different mixtures of rice husk and sawdust in their carbonized forms. Each group of briquettes, labeled A to E, reflects a variation in the ratio of rice husk to sawdust, demonstrating how these proportions influence the appearance, compactness, and structural integrity of the final product. Samples A, B, C, D, and E are prepared using the pellet ratio of SD and RH of 100: 0; 75: 25; 50: 50; 25: 75; and 0: 100, respectively. The visual differences observed in the figure indicate that the composition of the raw materials affects the molding and carbonization outcomes. Some briquettes, such as those in groups B and D, show rougher and less uniform surfaces, which may suggest weaker bonding or uneven compaction during formation. In contrast, briquettes in group E appear more uniform and well-formed, indicating a more balanced mixture that allows better compaction and cohesion during the production process. The consistency of color across all samples confirms successful carbonization, but the differences in texture and form highlight the varying quality and potential performance of each formulation. These physical characteristics are essential because they directly influence the mechanical durability, combustion efficiency, and practical applicability of the briquettes. Therefore, **Figure 3** provides a clear visual representation of how adjusting the mixture of rice husk and sawdust can lead to significant differences in briquette quality, which is critical for determining the most effective and efficient composition for fuel use.

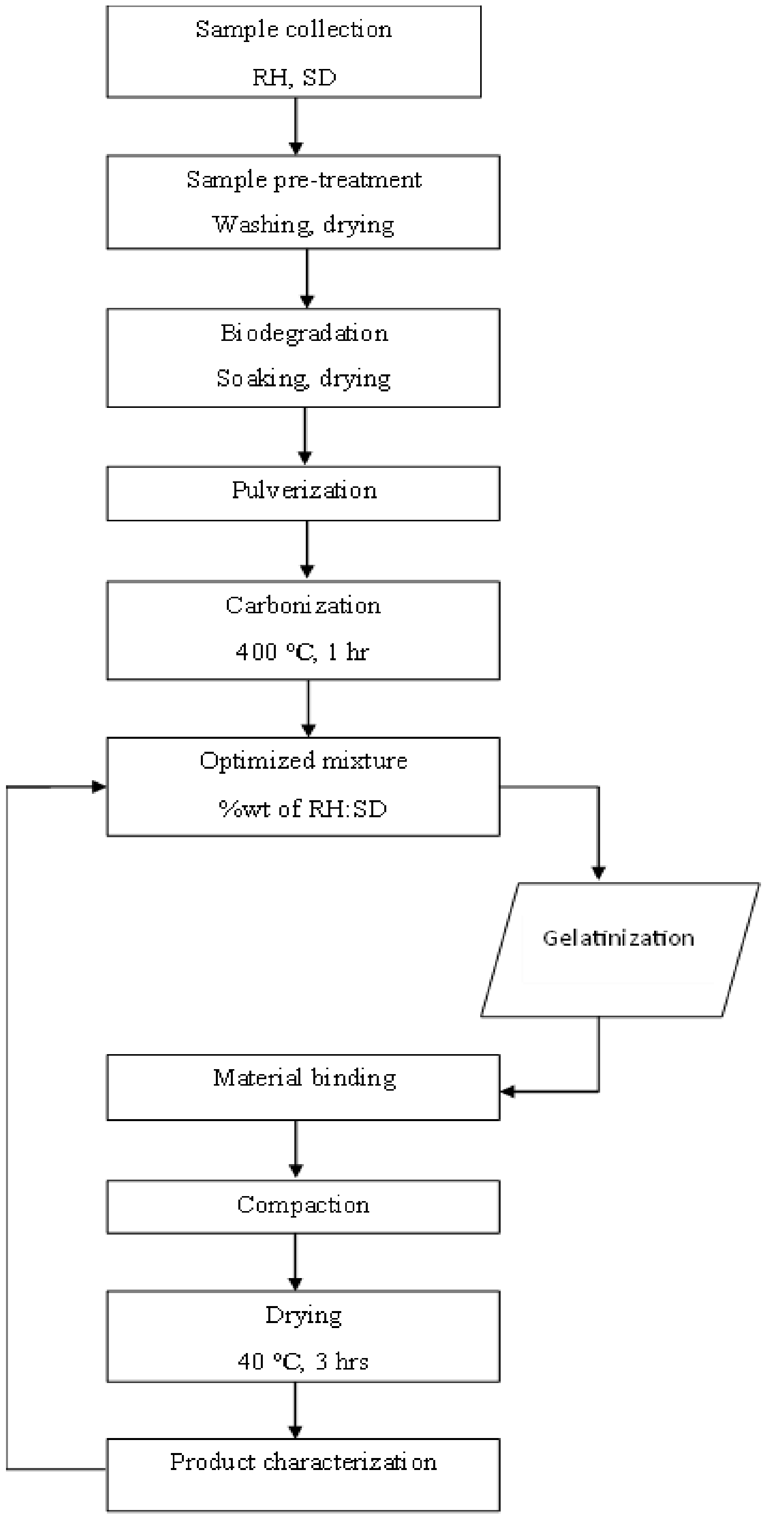

Figure 2. Process flow chart of briquette production from rice husk and saw dust mixtures.

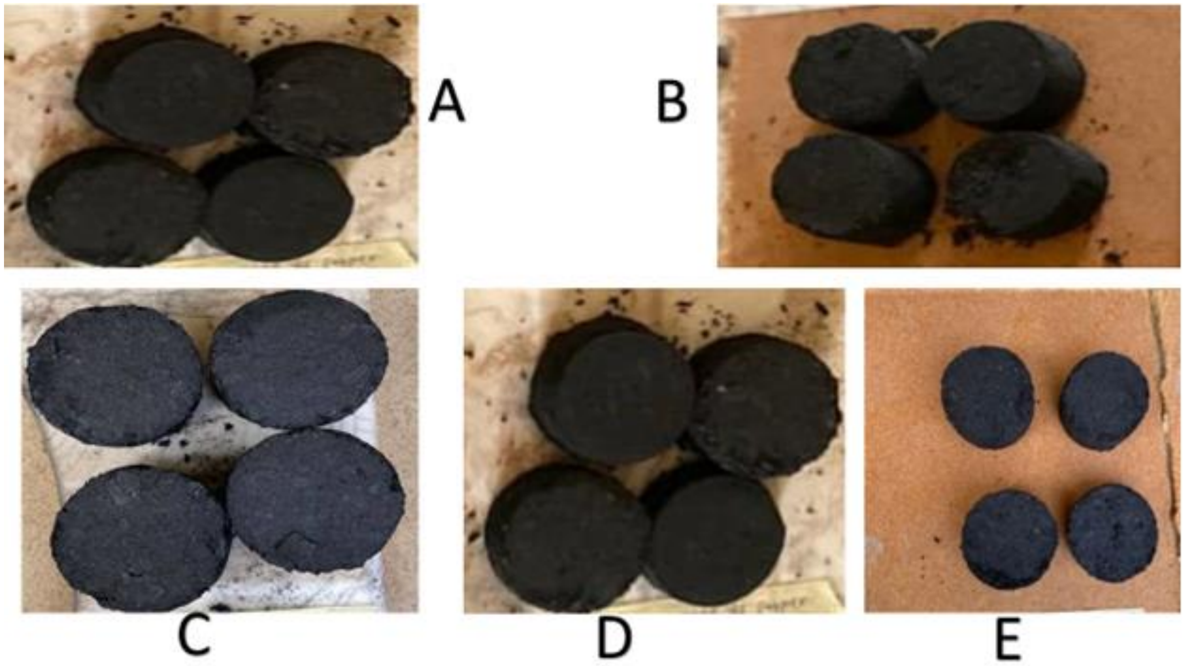

Figure 3. Briquettes produced from the variations of rice husk and sawdust mixture in their carbonized forms. Samples A, B, C, D, and E are prepared using the pellet ratio of SD and RH of 100: 0; 75: 25; 50: 50; 25: 75; and 0: 100, respectively.

3.1. Proximate Analysis of Pellets

The proximate analysis of the briquettes provides information on their performance and suitability for various applications. Each of the results of the proximate analysis for the varying compositions of sawdust and rice husk mixture, and the pure samples of a single entity are presented in **Table 2**.

Table 2. Proximate analysis of the pellets.

Pellet ratio (SD: RH)	Ash Content (%)	Moisture Content (%)	Fixed Carbon (%)	Volatile Matter (%)
100: 0	4.29	8.03	6.36	81.32
75: 25	7.26	7.65	6.62	78.47
50: 50	9.13	6.98	6.86	77.03
25: 75	12.26	7.12	7.16	73.46
0: 100	15.99	6.60	7.42	69.99

The calorific value of a briquette depends on the value of its moisture content (MC). A low moisture content suggests a higher calorific value for most fuel substances (Abdel Aal *et al*., 2023; Rahman *et al*., 2024; Waweru & Chirchir, 2017). As shown in Table 2, the percentage MC for different pellets shows that the RH pellet (100 % RH) had the lowest MC (6.60 %), while the SD pellet (100 % SD) had the highest percentage MC (8.03 %). This suggests that pure SD retained more water than RH. Higher MC can affect combustion efficiency, as more energy would be required to evaporate water from the material. The percentage MC recorded for RH indicates that it has a lower water retention capacity. This could contribute to a more efficient combustion process. For the optimized pellets, it was found that the MC value is directly proportional to the mass fraction of SD in the mixture; at 0.75 wt% SD, the MC decreased from 7.60 % to 6.98 % at 0.50 wt% SD. However, at 0.25 wt% SD, the moisture content slightly increased to 7.12 %. This could be due to the combined effects of both materials, where an optimal value at 0.50 wt% SD and RH is reached for lower moisture to occur. Standard values of MC in agricultural residues and sawdust recommended for both storage and combustion purposes as 15 % and 12-20%, respectively (Akowuah *et al*., 2012).

Ash matter is found to negatively affect heat transfer to the surface of the fuel, as well as oxidation of the fuel during combustion (Staničić *et al*., 2022). Lower ash content offers higher heating value for briquettes, while higher ash content results in particulate emissions, consequently leading to atmospheric pollution. Higher ash content could also affect combustion volume and efficiency (Inegbedion & Ikpoza, 2022). **Table 2** revealed that 100 % RH pellets had the highest ash content of 15.99 %, while pellets produced from 100 % SD had the lowest percentage of 4.29 %. This shows that 100 % SD produces minimal residue after combustion, thus, making it most suitable for applications where frequent cleaning is less desired. On the other hand, 100 % RH gave the most non-combustible residue, thus, leading to more maintenance and cleaning in combustion systems. It was observed from the results that as the mass fraction of RH increases, the ash content increases steadily from 7.26% (0.25 wt% RH) to 12.26% (0.75 wt % RH). Hence, a higher RH composition results in higher ash content; suggesting a trade-off between the material's abundance and fuel quality.

The volatile matter (VM) of biomass residues is estimated between 70% to 86% as similarly reported by Yahya *et al*. (2023). Values recorded for VM for both optimized and pure pellets are within the range of 69.00 % - 81.32 %. Biomass of more than 30 % volatile matter provides stability and flammability due to the de-volatization phase than other fuels such as coal (Saeed *et al*., 2016; Wang *et al*., 2021). **Table 2** also shows the percentage values of VM present in the pure and optimized pellets. Pure SD pellets gave the highest value of VM (81.32 %), indicating a high proportion of lignocellulosic compounds in the material that contributes to the initial ignition and combustion process. Contrastingly, a lower VM (69.99 %) was obtained for pure RH pellet, which indicates fewer hemicellulose in the compounds. This makes the former an excellent material for quick ignition, while the latter is applicable for a slower ignition process for a more sustained burning. For the optimized pellets, VM decreases as the proportion of RH increases, from 78.47 % at 0.25 wt % RH to 73.46 % at 0.75 wt % RH. This confirms that a higher portion of RH in the briquettes might result in a more controlled and sustained combustion, even as the ignition is slowed down.

The fixed carbon (FC) of a briquette is the percentage of carbon (solid fuel) available for combustion after the volatile matter is distilled off, which also determines the calorific value of a fuel (Islam *et al*., 2019). In this study, there was a 16.67 % increase of FC higher proportions of RH pellets; Higher FC indicates higher energy content and thus, a longer burn time, making RH-rich briquettes potentially more efficient. SD-rich briquettes have slightly lower fixed carbon, suggesting a shorter burn time but potentially higher flame temperatures due to higher volatile matter. Fixed carbon also gives a rough estimate of the heating value of fuel and acts as the main heat generator during burning.

3.2. Calorific Value Analysis of Pellets

The result of the calorific value (CV) are presented in **Figure 4** and **Table 3**. The CV is the energy content of fuel per unit mass or volume. It is the heat liberated by the complete combustion of a unit quantity of fuel at a standard state (Bukkarapu & Krishnasamy, 2022). The most significant property of a fuel is its CV, thus, the higher the CV, the more efficient its burning rate (Onochie *et al*., 2020), which implies that more thermal energy is released during combustion (Akpenpuun *et al*., 2020). From **Table 2**, the CV showed that the pellets from 100 % RH pellets had the highest CV (2658.77 kJ/kg) while 100% SD pellets had the lowest (18509.84 kJ/kg). It was also observed from the optimized pellets that for the 50:50

SD/RH pellet, the lowest calorific value of 16,722.69 (kJ/kg) was obtained, while the 25:75 SD/RH gave the highest calorific value of 20422.74 kJ/kg. Overall, the results of CV, fixed carbon and moisture content presented in **Tables 2 and 3** confirms the findings of Rahman *et al.* (2024), Waweru *et al.* (2017), Abdel Aal *et al.* (2023) and Islam *et al.* (2019), who stated that a typical fuel with low MC and high FC implies a high CV.

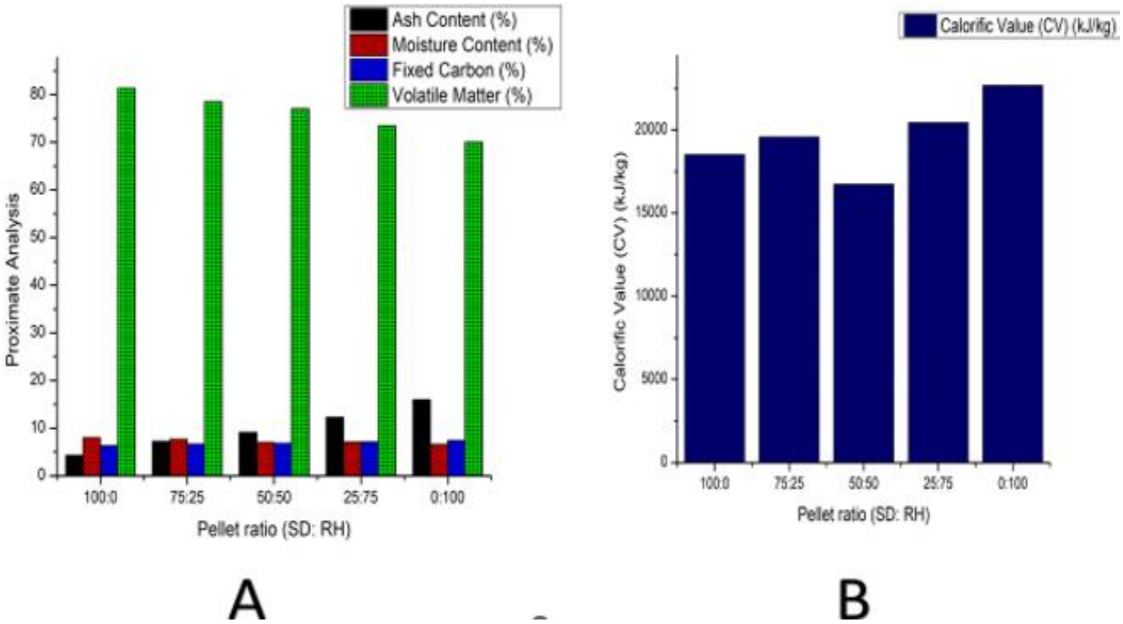

Figure 4. Proximate Analysis (Figure A) and Calorific Value (Figure B)

Table 3. Calorific value of briquettes.

Pellet ratio (SD: RH)	Calorific Value, CV (kJ/kg)
100: 0	18509.84
75: 25	19564.87
50: 50	16722.69
25: 75	20422.74
0: 100	22658.77

3.3. Burning Rate (BR)

The result of the burning rate (BR) is presented in **Figure 5** and **Table 4**. The BR of the briquettes is an important indicator of how a certain mass of fuel is combusted in the air, which is directly linked to the CV of the particular material (Mohammed *et al*., 2015).

The CV obtained showed that a lower CV obtained for pure SD pellets implies a relatively lower energy release during combustion, which corresponds to a lower burning rate. The burning rate value of 0.0015 $gmin^{-1}$ for 100 % SD confirms a slower and less intense combustion process that naturally occurs when the energy content is lowered. According to Onuegbu *et al.* (2011), the burning rate can be affected by particle composition and properties, and this was reflected in the optimized pellets when SD was mixed with RH in varying proportions, thus, affecting the burning rate significantly. At 50:50 SD/RH, the pellet mixture shows a burning rate of 0.0030 $gmin^{-1}$, which corresponds with the lower CV (16,722.69 kJ/kg) observed in this mix. Higher BR derived at this mixing ratio suggests a more rapid combustion process. However, a decrease in CV at this particular ratio indicates that while the burning rate increases, the overall energy content decreases, with a probable balance between the higher CV of RH and the lower CV of SD. Similarly, for the 25:75 SD/RH, BR is significantly lower (0.0006 gmin^{-1}), even as the calorific value is higher at 20,422.74 kJ/kg. This indicates that while the energy content per unit mass is higher, the combustion process may be less efficient or slower due to the increased proportion of RH, which might have different combustion characteristics such as particle size, density, or ash content than SD, while consequently affecting the burn rate.

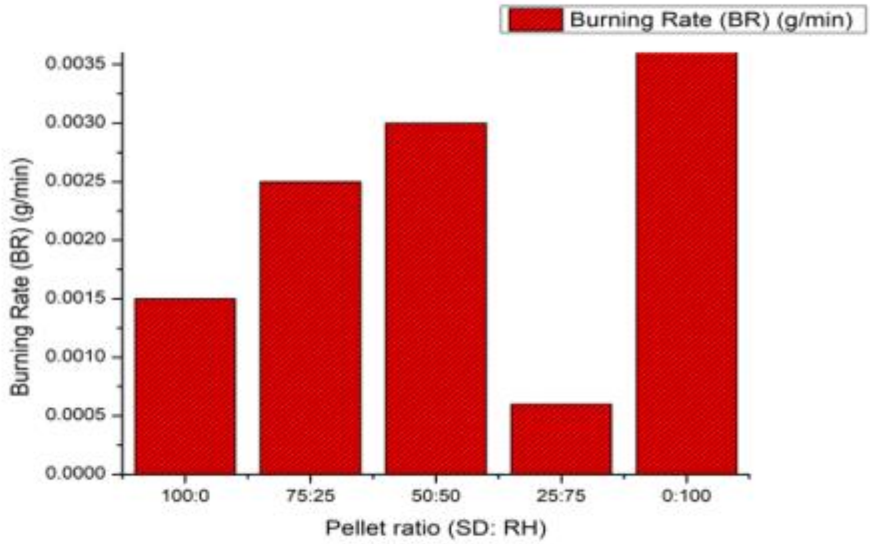

Figure 5. Burning rate of briquettes produced from various pellet mixtures.

Table 4. Burning rate of briquettes.

SD: RH	Burning Rate, BR (g/min)
100:0	0.0015
75:25	0.0025
50:50	0.0030
25:75	0.0006
0:100	0.0039

4. CONCLUSION

Findings in this study have revealed that the fuel properties of pellets made from sawdust (SD) and rice husk (RH) depend significantly on varying mixing ratios. Pure sawdust pellets (100 % SD) offered quick ignition and minimal ash residue but had a lower calorific value and slower burning rate. In contrast, pure rice husk pellets (100 % RH) exhibited the highest calorific value but gave the lowest moisture content; making both materials rightly efficient for energy generation but requiring extra maintenance due to higher ash content. However, optimized pellet mixtures provided a balance between these extremes. More specifically, the 50:50 SD/RH mixture, while having a lower calorific value, presented the highest burning rate, hence, indicating a faster but less efficient combustion process. The 25:75 wt.% SD/RH pellet also yielded the highest calorific value among the optimized mixtures, even as it gave a slower burn rate. These findings suggest that the optimal selection of SD and RH ratios can adjust the pellets for specific energy needs, thus, balancing efficiency, burn duration, and ease of use. Hence, this study is useful for the development of sustainable and efficient biofuel sources.

5. ACKNOWLEDGMENT

This research was not funded by any specific grant from agencies in the public, private, or non-profit sectors.

6. AUTHORS' NOTE

The authors declare that there is no conflict of interest regarding the publication of this article. Authors confirmed that the paper was free of plagiarism.

7. REFERENCES

Abdel Aal, A. M., Ibrahim, O. H., Al-Farga, A., and El Saeidy, E. A. (2023). Impact of biomass moisture content on the physical properties of briquettes produced from recycled *ficus nitida* pruning residuals. *Sustainability*, *15*(15), 11762.

Abdurrahman, M. I., Chaki, S., and Saini, G. (2020). Stubble burning: Effects on health & environment, regulations and management practices. *Environmental Advances*, *2*, 100011.

Adewumi, A., Olu-lawal, K. A., Okoli, C. E., Usman, F. O., and Usiagu, G. S. (2024). Sustainable energy solutions and climate change: A policy review of emerging trends and global responses. *World Journal of Advanced Research and Reviews*, *21*(2), 408-420.

Agunloye, O. O. M., Kolawole, A. O., Adesakin, M. F., Arowolaju, O. O., and Israel, J. (2020). Economic and environmental implications of charcoal production in Kogi State, Nigeria. *World Rural Observations*, *12*, 47-55.

Ahmad, T., and Zhang, D. (2020). A critical review of comparative global historical energy consumption and future demand: The story told so far. *Energy Reports*, *6*, 1973-1991.

Akhter, F., Soomro, S. A., Jamali, A. R., Chandio, Z. A., Siddique, M., and Ahmed, M. (2021). Rice husk ash as green and sustainable biomass waste for construction and renewable energy applications: A review. *Biomass Conversion and Biorefinery*, 1-11.

Akolgo, G. A., Awafo, E. A., Essandoh, E. O., Owusu, P. A., Uba, F., and Adu-Poku, K. A. (2021). Assessment of the potential of charred briquettes of sawdust, rice and coconut husks: Using water boiling and user acceptability tests. *Scientific African*, *12*, e00789.

Akowuah, J. O., Kemausuor, F., and Mitchual, S. J. (2012). Physico-chemical characteristics and market potential of sawdust charcoal briquette. *International Journal of Energy and Environmental Engineering*, *3*, 1-6.

Akpenpuun, T. D., Salau, R. A., Adebayo, A. O., Adebayo, O. M., Salawu, J., & Durotoye, M. (2020). Physical and combustible properties of briquettes produced from a combination of groundnut shell, rice husk, sawdust and wastepaper using starch as a binder. *Journal of Applied Sciences and Environmental Management*, *24*(1), 171-177.

Alabi, O. O., Adeyi, T. A., and Ekun, S. K. (2024). Experimental analysis and combustion characteristics of briquettes from different wood in Nigeria. *Engineering and Technology Journal*, *42*(07), 833-840.

Ali, B., Saadun, N., Kamarudin, N., Alias, M. A., Nawi, N. M., and Azhar, B. (2023). Fuelwood value chain in Northern Nigeria: Economic, environment, and social sustainability concerns. *Forests*, *14*(5), 906.

Ayodele, O. P., and Aluko, O. A. (2017). Weed management strategies for conservation agriculture and environmental sustainability in Nigeria. *IOSR Journal of Agriculture and Veterinary Science*, *10*(8), 1-8.

Banerjee, N. (2023). Biomass to energy—an analysis of current technologies, prospects, and challenges. *BioEnergy Research*, *16*(2), 683-716.

Bot, B. V., Tamba, J. G., and Sosso, O. T. (2024). Assessment of biomass briquette energy potential from agricultural residues in Cameroon. *Biomass Conversion and Biorefinery*, *14*(2), 1905-1917.

Bukkarapu, K. R., and Krishnasamy, A. (2022). A critical review on available models to predict engine fuel properties of biodiesel. *Renewable and Sustainable Energy Reviews*, *155*, 111925.

Chomini, E. A., Henry, M. U., Daspan, A. J., Agbaje, I. O., Ameh, M. A., Osasebor, F. O., and Chomini, M. S. (2022). Perception of the impact of fuel wood and charcoal productions on the environment: A case study of toro LGA of bauchi state, Nigeria. *Journal of Applied Sciences and Environmental Management*, *26*(10), 1665-1668.

Ekpo, A., and Mba, E. (2020). Assessment of commercial charcoal production effect on Savannah Woodland of Nasarawa State, Nigeria. *Journal of Geography, Environment and Earth Science International*, *24*, 74-82.

Elehinafe, F. B., and Okedere, O. B. (2023). Fuel-briquetting for sustainable development in developing countries-A review. *Advances in Environmental and Engineering Research*, *4*(3), 1-13.

Giwa, A., Alabi, A., Yusuf, A., and Olukan, T. (2017). A comprehensive review on biomass and solar energy for sustainable energy generation in Nigeria. *Renewable and Sustainable Energy Reviews*, *69*, 620-641.

Hamzat, A., Gombe, S. Y., and Pindiga, Y. (2019). Briquette from Agricultural Waste a Sustainable Domestic Cooking Energy. *Gombe Technical Education Journal*, *12*(1), 63-69.

Hroncová, E., Ladomerský, J., Valíček, J., and Dzurenda, L. (2016). Combustion of biomass fuel and residues: Emissions production perspective. *Developments in Combustion technology*, *1*, 1-32.

Inegbedion, F. (2022). Estimation of the moisture content, volatile matter, ash content, fixed carbon and calorific values of saw dust briquettes. *MANAS Journal of Engineering*, *10*(1), 17-20.

Islam, S., Hossen, M. A., Huda, M., Paul, H., and Bhuiyan, M. (2019). Prospect of rice straw biomass briquette production: An alternative source of energy. *Journal of Agricultural Engineering, 42*(3), 79-86.

Ivanova, T., Havrland, B., Hutla, P., and Muntean, A. (2012). Drying of cherry tree chips in the experimental biomass dryer with solar collector. *Research in Agricultural Engineering*, *58*(1), 16-23.

Japhet, J. A., Luka, B. S., Maren, I. B., and Datau, S. G. (2020). The potential of wood and agricultural waste for pellet fuel development in Nigeria—A technical review. *International Journal of Engineering Applied Sciences and Technology*, *4*, 598-607.

Jiang, K., Xing, R., Luo, Z., Huang, W., Yi, F., Men, Y., and Shen, G. (2024). Pollutant emissions from biomass burning: A review on emission characteristics, environmental impacts, and research perspectives. *Particuology*, *85*, 296-309.

Jume, H. I., Alhaji, B. Y., Ahmadu, U., Ibrahim, S. O., Agida, M., Muazu, A., and Abdulkadir, B. (2024). Production of briquettes from a blend of rice husks and palm kernel shells as an alternative solid fuel. *FUDMA Journal of Sciences*, *8*(3), 353-360.

Łaska, G., and Ige, A. R. (2023). A review: Assessment of domestic solid fuel sources in Nigeria. *Energies*, *16*(12), 4722.

Maina, Y. B., Umar, N. K., and Egbedimame, A. B. (2020). An empirical analysis of the impact of household fuel wood consumption on the environment in Nigeria. *FUTY Journal of the Environment*, *14*(3), 35-46.

Marreiro, H. M., Peruchi, R. S., Lopes, R. M., Andersen, S. L., Eliziário, S. A., and Rotella Junior, P. (2021). Empirical studies on biomass briquette production: A literature review. *Energies*, *14*(24), 8320.

Maxwell, D., Gudka, B. A., Jones, J. M., and Williams, A. (2020). Emissions from the combustion of torrefied and raw biomass fuels in a domestic heating stove. *Fuel Processing Technology*, *199*, 106266.

Maxwell, D., Gudka, B. A., Jones, J. M., & Williams, A. (2020). Emissions from the combustion of torrefied and raw biomass fuels in a domestic heating stove. *Fuel Processing Technology*, *199*, 106266.

Mohammed, T. I., and Olugbade, T. O. (2015). Burning rate of briquettes produced from rice bran and palm kernel shells. *International Journal of Material Science Innovations*, *3*(2), 68-73.

Niambe, O. K., Gbaa, E. N., Niambe, R. S., Ityowuhe, G. T., and Kaa, A. E. (2024). Evaluation of charcoal usage and its influence on deforestation in Makurdi Metropolis Benue State, Nigeria. *American Journal of Environment and Climate*, *3*(2), 9-17.

Obi, O. F., Olugbade, T. O., Orisaleye, J. I., & Pecenka, R. (2023). Solid biofuel production from biomass: Technologies, challenges, and opportunities for its commercial production in Nigeria. *Energies*, *16*(24), 7966.

Odejobi, O. J., Ajala, O. O., and Osuolale, F. N. (2024). Review on potential of using agricultural, municipal solid and industrial wastes as substrates for biogas production in Nigeria. *Biomass Conversion and Biorefinery*, *14*(2), 1567-1579.

Ofori, P. (2020). Production and characterisation of briquettes from carbonised cocoa pod husk and sawdust. *Open Access Library Journal*, *7*(02), 1-20.

Okey, S. N. (2023). The use of agricultural wastes as renewable energy resources: A review. *Nigerian Journal of Animal Science and Technology (NJAST)*, *6*(2), 23-34.

Oloyede, A. A., Faruk, N., Noma, N., Tebepah, E., and Nwaulune, A. K. (2023). Measuring the impact of the digital economy in developing countries: A systematic review and meta-analysis. *Heliyon*, *9*(7), 1-19.

Onochie, U. P., Aliu, S. A., Nosegbe, U., and Adama, K. K. (2020). Comparative study and experimental analysis of pellets from biomass sawdust and rice husk. *Journal of Advances in Science and Engineering*, *3*(2), 85-90.

Onuegbu, T., Ekpunobi, U., Ekeoma, M., Ogbu, I., and Obumselu, O. (2011). Comparative studies of ignition time and water boiling test of coal and biomass briquettes blend. *Internal Journal of Research and Review in Applied Sciences (IJRRAS)*, *7*, 153-159.

Pradhan, P., Sinha, A. K., and Pandit, T. K. (2024). The effect of stubble burning and residue management on soil properties: A review. *International Journal of Plant and Soil Science*, *36*(6), 36-49.

Rahimi, Z., Anand, A., and Gautam, S. (2022). An overview on thermochemical conversion and potential evaluation of biofuels derived from agricultural wastes. *Energy Nexus*, *7*, 100125.

Rahman, A., Marufuzzaman, M., Street, J., Wooten, J., Gude, V. G., Buchanan, R., and Wang, H. (2024). A comprehensive review on wood chip moisture content assessment and prediction. *Renewable and Sustainable Energy Reviews*, *189*, 113843.

Ríos-Badrán, I. M., Luzardo-Ocampo, I., García-Trejo, J. F., Santos-Cruz, J., and Gutiérrez-Antonio, C. (2020). Production and characterization of fuel pellets from rice husk and wheat straw. *Renewable Energy*, *145*, 500-507.

Saeed, M. A., Andrews, G. E., Phylaktou, H. N., and Gibbs, B. M. (2016). Global kinetics of the rate of volatile release from biomasses in comparison to coal. *Fuel*, *181*, 347-357.

Singh, G. (2024). The environmental impact of Stubble burning. *International Journal of Science and Research Archive*, *12*(2), 114-116.

Stanicic, I., Brorsson, J., Hellman, A., Mattisson, T., and Backman, R. (2022). Thermodynamic analysis on the fate of ash elements in chemical looping combustion of solid fuels– iron-based oxygen carriers. *Energy and Fuels*, *36*(17), 9648-9659.

Tayeh, B. A., Alyousef, R., Alabduljabbar, H., and Alaskar, A. (2021). Recycling of rice husk waste for a sustainable concrete: A critical review. *Journal of Cleaner Production*, *312*, 127734.

Ullah, S., Noor, R. S., Sanaullah, and Gang, T. (2021). Analysis of biofuel (briquette) production from forest biomass: A socioeconomic incentive towards deforestation. *Biomass Conversion and Biorefinery*, *13*, 1-15.

Wang, J., and Azam, W. (2024). Natural resource scarcity, fossil fuel energy consumption, and total greenhouse gas emissions in top emitting countries. *Geoscience frontiers*, *15*(2), 101757.

Wang, Y., Yan, B., Wang, Y., Zhang, J., Chen, X., & Bastiaans, R. J. (2021). A comparison of combustion properties in biomass–coal blends using characteristic and kinetic analyses. *International Journal of Environmental Research and Public Health*, *18*(24), 12980.

Waweru, J., & Chirchir, D. K. (2017). Effect of the briquette sizes and moisture contents on combustion characteristics of composite briquettes. *International Journal of Innovative Science, Engineering and Technology*, *4*(7), 102-111.

Yahya, A. M., Adeleke, A. A., Nzerem, P., Ikubanni, P. P., Ayuba, S., Rasheed, H. A., and Paramasivam, P. (2023). Comprehensive characterization of some selected biomass for bioenergy production. *ACS omega*, *8*(46), 43771-43791.

Yunusa, S. U., Mensah, E., Preko, K., Narra, S., Saleh, A., and Sanfo, S. (2024). A comprehensive review on the technical aspects of biomass briquetting. *Biomass Conversion and Biorefinery*, *14*(18), 21619-21644.