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Comparative Evaluation of Fuel Properties and Energy Potential of Pellets Produced From Diverse Agricultural Biomass Wastes in Tropical Regions: Implications for Sustainable Bioenergy Production

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ABSTRACT

This study presents a comparative evaluation of the calorific value and proximate composition of pellets produced from eight different agricultural biomass wastes: palm kernel fruit bunch (PKFB), coconut fruit bunch (CFB), rice husk (RH), groundnut shell (GNS), sugarcane bagasse (SB), palm kernel shell (PKS), coconut shell (CS), and sawdust (SD). The biomass samples were collected, processed, and pelletized under identical conditions before characterization. Experimental results showed significant variations in fuel properties. Palm kernel shell and coconut shell pellets exhibited the highest calorific values (20.1 MJ/kg and 19.6 MJ/kg, respectively), the lowest ash contents (2.4% and 1.9%), and the highest fixed carbon (18.2% and 20.8%). In contrast, rice husk pellets recorded the lowest calorific value (15.3 MJ/kg) due to exceptionally high ash content (18.5%). All samples maintained acceptable moisture levels (less than 12%), while volatile matter contents were generally high (over 69%), indicating good ignition properties. The findings demonstrate that palm kernel shell and coconut shell are the most promising feedstocks for high-quality biomass pellets, offering superior energy density and combustion characteristics. The study highlights the potential of locally available agro-industrial residues for sustainable bioenergy production and underscores the importance of selecting feedstocks and conducting comprehensive fuel characterization in biomass pellet development.

Keywords: Biomass Pellets, Calorific Value, Proximate Analysis, Agricultural Waste, Palm Kernel Shell, Coconut Shell, Renewable Energy, Bioenergy

INTRODUCTION

Biomass pellets have emerged as a promising renewable energy source, offering a sustainable alternative to fossil fuels for heat and power generation. The use of agricultural and agro-industrial waste for pellet production not only addresses waste management challenges but also supports carbon-neutral energy systems and rural economic development (Ighodaro *et al*., 2023; Jagtap & Kalbande 2023; Onochie *et al*., 2025; Erokare *et al*., 2026). In regions with abundant agricultural residues, such as Nigeria and other tropical countries, converting these materials into densified pellets offers significant opportunities for clean energy production (Winter *et al*., 2026; Halim *et al*., 2020).

The quality of biomass pellets is primarily determined by their proximate and ultimate analyses, including calorific value, moisture content, volatile matter, ash content, and fixed carbon. These properties directly influence combustion efficiency, emission profiles, slagging/fouling tendencies, and overall techno-economic viability (Umubigho et al., 2026; Anuchi *et al*., 2022; Anwar *et al*., 2014). High calorific value, low moisture and ash contents, and balanced volatile matter are generally desired for optimal performance in boilers and gasifiers.

Despite the growing interest in biomass pelletization, there remains limited comparative data on the fuel properties of various locally available agricultural wastes in pellet form, particularly in developing countries. Most previous studies have focused on individual biomass types or common woody residues, with fewer comprehensive evaluations of diverse tropical agricultural by-products under identical processing conditions (Bazargan *et al*., 2020; Halim *et al*., 2020).

This study investigates the calorific value and proximate composition of pellets produced from eight different agricultural biomass wastes: Palm kernel fruit bunch (PKFB), Coconut fruit bunch (CFB), rice husk (RH), Groundnut shell (GNS), sugarcane bagasse (SB), palm kernel shell (PKS), Coconut shell (CS), and Sawdust (SD). The objective is to evaluate their potential as solid biofuels by comparing key fuel properties and identifying the most promising feedstocks for energy applications. The findings are expected to provide valuable insights for the development of sustainable biomass energy systems in resource-rich agricultural regions.

MATERIALS AND METHODS

Material Collection

Eight different biomass samples of agricultural waste were collected from dumpsites. These samples are Palm kernel fruit bunch (PKFB), Coconut fruit bunch (CFB), rice husk (RH), Groundnut shell (GNS), sugarcane bagasse (SB), palm kernel shell (PKS), Coconut shell (CS), Sawdust (SD)

Material Preparation

After collecting the samples, they were sifted and washed to remove contaminants, sun-dried for 1 week to reduce moisture content, pulverized, and compressed at 50 MPa using a hydraulic press to form pellets. Thereafter, the samples were taken for experimental analysis.

Method

Calorific Value

5g of the sample was weighed and carefully placed in a combustion crucible inside the bomb. The bomb was filled with oxygen at high pressure (approximately 25-30 atm). The bomb was submerged in a mass of water and ignited by an electric spark. The initial and the final temperature of the water were recorded, and the temperature rise was generated automatically in MJ/Kg

$$\mathrm{CV} = \frac{(W+w)\times\Delta T}{m} \quad (1)$$

W = water equivalent of the calorimeter (mass x specific heat of water)
w = Mass of water in the calorimeter
ΔT = rise in water temperature (^{O}C)
m = mass of fuel (g)
Bomb Calorimeter Sunny 5200 Model equipment was used for this experiment.

Proximate Analysis of Biomass Sample

For the proximate analysis, the Steriox model equipment was used. This entails the physical properties of the fuel pellets, including moisture, ash, volatile matter, and fixed carbon.

i Volatile matter of fuel sample (VM): A clean, dry and weighed empty crucible was noted as (W1). 1g of the sample was placed in a crucible and noted as (W2). This was covered with a lid and placed in a preheated furnace at 950 °C for 10 minutes to ensure complete combustion. It was removed and cooled in a desiccator and weighed as (W3). The results were obtained.

Calculation:

$$\mathrm{VM} = \frac{(W2-W3)}{(W2-W1)} x\ 100 \quad (2)$$

W1- weight of empty crucible
W2- weight of crucible+ dry sample
W3- weight of crucible+ residue after heating

ii Ash content of fuel sample (AS): A clean, dry and weighed empty crucible was noted as (W1). 1g of sample was placed in a crucible (W2) and heated to 700 °C in a furnace for 1 hour to complete combustion, until a whitish appearance was observed. It was removed and cooled in a desiccator. The ash and the crucible were weighed and noted as (W3). The results were obtained.

Calculation: $$\mathrm{AC} = \frac{(\mathrm{W2}-\mathrm{W3})}{(\mathrm{W2}-\mathrm{W1})} x\ 100 \quad (3)$$

iv Moisture content analysis (MC): Gallenkhamp model was used to determine the moisture content. A clean, dry and weighed empty container was noted as (W1). 1g of the sample was placed in a container and noted as (W2). This was placed in a hot-air oven at 105 °C for 1 hour until a constant weight was obtained for complete combustion. It was removed and cooled in a desiccator and weighed as (W3). The results were obtained.

Calculation: $$\mathrm{MC} = \frac{(\mathrm{W2}-\mathrm{W3})}{(\mathrm{W2}-\mathrm{W1})} x\ 100 \quad (4)$$

W1- weight of empty container
W2- weight of container+ wet sample
W3- weight of container+ dry sample

iii Fixed carbon of fuel sample (FC): The fixed carbon was determined using the formula.

$$FC = 100 - (\%VM + \%AC + \%MC) \quad (5)$$

Where VM, AC and MC are volatile matter, ash content and moisture content, respectively.

RESULTS AND DISCUSSION

Calorific Values Results Biomass

The calorific values of eight pelletized biomass samples, determined experimentally and presented in the table alongside Figure 1, ranged from 15.3 MJ/kg for rice husk (RH) to 20.1 MJ/kg for palm kernel shell (PKS). These values fall within the typical range reported for densified lignocellulosic biomass pellets (Winter *et al.*, 2026; Halim *et al*., 2020).

Palm kernel shell (PKS) exhibited the highest calorific value at 20.1 MJ/kg, followed by coconut shell (CS) at 19.6 MJ/kg. The superior energy content of these shell-based materials is attributable to their elevated fixed carbon content (18.2% for PKS and 20.8% for CS) and low ash fractions (2.4% and 1.9%, respectively) (Asaad *et al*., 2023; Winter *et al*., 2026). In contrast, rice husk (RH) recorded the lowest calorific value of 15.3 MJ/kg, primarily due to its high ash content (18.5%), which consists predominantly of silica, thereby reducing the combustible fraction (Diego *et al.*, 2024; Samarjeet *et al.*, 2021).

Moderate calorific values were observed for sawdust (SD) at 18.4 MJ/kg, groundnut shell (GNS) at 17.9 MJ/kg, coconut fruit bunch (CFB) at 17.4 MJ/kg, sugarcane bagasse (SB) at 16.8 MJ/kg, and palm kernel fruit bunch (PKFB) at 16.7 MJ/kg. Sawdust demonstrated favourable characteristics, notably a low ash content (1.1%) (Winter *et al*., 2026). A strong positive correlation was identified between calorific value and fixed carbon content, alongside an inverse relationship with ash content. These relationships are consistent with established thermochemical principles in biomass fuel evaluation (Halim *et al*., 2020).

The experimental findings are well supported by Halim *et al*. (2020) and Winter *et al*. (2026), which documented calorific values of 19.0–21.5 MJ/kg for palm kernel shell and 18.5–21.0 MJ/kg for coconut shell, respectively. Asaad *et al*. (2023) have similarly reported high energy potential for shell-based biomass pellets. Research confirms the lower heating values typically observed for rice husk pellets (14.5–16.5 MJ/kg) due to their elevated silica ash content (Diego *et al*., 2024; Samarjeet *et al*., 2021). Among the biomass types evaluated, palm kernel shell and coconut shell pellets offer the greatest potential as high-energy-density solid biofuels. The results highlight the critical role of feedstock selection in biomass pellet production and support the sustainable valorization of agro-industrial residues for renewable energy applications. High-ash materials, such as rice husks, may require additional pretreatment to enhance their fuel properties.

Table 1: Calorific Value Results of Biomass

Biomass Type	Calorific Values (MJ/Kg)
Palm kernel fruit bunch (PKFB)	16.7
Coconut fruit bunch (CFB)	17.4
Rice husk (RH)	15.3
Groundnut shell (GNS)	17.9
Sugarcane bagasse (SB)	16.8
Palm kernel shell (PKS)	20.1
Coconut shell (CS)	19.6
Sawdust (SD)	18.4

Table 2: Proximate Analysis Results of Biomass

Biomass Type	Moisture Content (%)	Volatile Matter (%)	Ash Content (%)	Fixed Carbon (%)
Palm kernel fruit bunch (PKFB)	10.2	73.5	8.8	13.8
Coconut fruit bunch (CFB)	9.8	75.2	4.3	15.1
Rice husk (RH)	8.4	69.8	18.5	11.7
Groundnut shell (GNS)	9.1	73.9	5.7	15.8
Sugarcane bagasse (SB)	10.5	77.6	4.8	13.9
Palm kernel shell (PKS)	9.3	77.8	2.4	18.2
Coconut shell (CS)	8.2	73.9	1.9	20.8
Sawdust (SD)	7.9	79.5	1.1	15.7

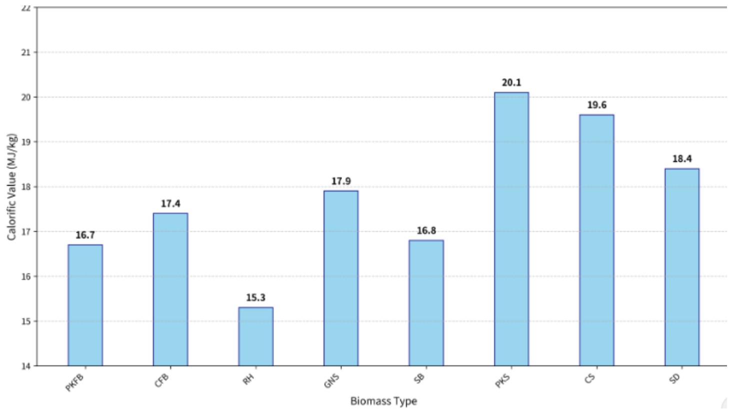

Figure 1: Calorific Values of Different Biomass Types

Moisture Content (%) Analysis

The moisture content of the eight pelletized biomass samples, determined experimentally and presented in Table 2 alongside Figure 2, ranged from 7.9% (sawdust) to 10.5% (sugarcane bagasse). All samples maintained moisture levels below 12%, which complies with typical quality standards for biomass pellets intended for thermal applications, as elevated moisture reduces net calorific value and combustion efficiency (Ighodaro *et al*., 2023; Jagtap & Kalbande 2023).

Sawdust (SD) exhibited the lowest moisture content at 7.9%, followed by coconut shell (CS) at 8.2% and rice husk (RH) at 8.4%. These lower values reflect effective drying during pelletization and the relatively low hygroscopicity of the raw materials. In comparison, sugarcane bagasse (SB) recorded the highest moisture content at 10.5%, followed by palm kernel fruit bunch (PKFB) at 10.2%. Palm kernel shell (PKS), coconut fruit bunch (CFB), and groundnut shell (GNS) showed moderate moisture levels of 9.3%, 9.8%, and 9.1%, respectively. The variations in moisture content are influenced by the structural characteristics and fibre composition of the original biomass, as well as the pelletization parameters employed. Lower moisture in woody and shell-based pellets (e.g., SD and CS) is particularly beneficial, improving combustion performance and enhancing storage stability (Jagtap & Kalbande 2023; Orhorhoro *et al*., 2024; Erokare *et al*., 2026).

These experimental results are consistent with Ighodaro *et al*. (2023) and Orhorhoro *et al*. (2024), who reported moisture contents for biomass pellets ranging from 6% to 12%, with shell-base feedstock often achieving lower values after optimized processing. Jagtap *et al*. (2022) documented low moisture content in sawdust and coconut-shell pellets. Onochie *et al*. (2024), Sanchumpu et al. (2024), and Hardianto *et al*. (2023) research confirms that fibrous agricultural residues, such as sugarcane bagasse and palm kernel fruit bunches, tend to retain slightly higher residual moisture. The moisture contents of all evaluated biomass pellets are within acceptable limits for fuel applications. Sawdust and coconut shell pellets present the most favourable moisture profiles, thereby enhancing their suitability for efficient bioenergy utilization. The findings highlight the importance of selecting feedstock and optimizing processes for developing high-quality biomass pellets for sustainable energy production.

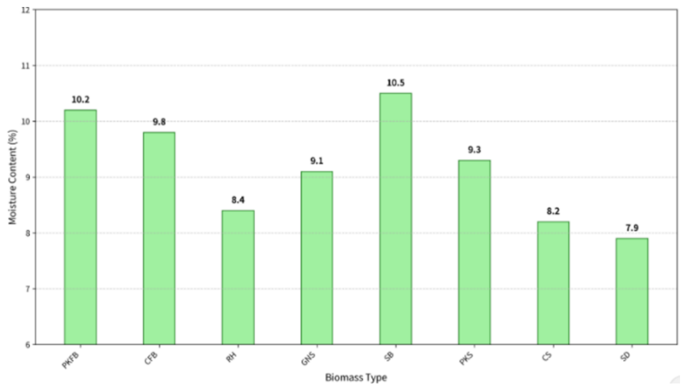

Figure 2: Moisture Content of Various Biomass Types

Volatile Matter (%) Analysis

The volatile matter content of the eight pelletized biomass samples, as determined experimentally and presented in Table 2 alongside Figure 3, ranged from 69.8% (rice husk) to 79.5% (sawdust). A high volatile matter content is a desirable characteristic of biomass fuels, as it facilitates easy ignition and rapid combustion (Abdulkadir, 2024; Abdulsalam *et al*., 2024). Sawdust (SD) exhibited the highest volatile matter content at 79.5%, followed by palm kernel shell (PKS) at 77.8% and sugarcane bagasse (SB) at 77.6%. These elevated values indicate strong potential for quick ignition and high combustion reactivity. In contrast, rice husk (RH) recorded the lowest volatile matter at 69.8%. The remaining samples showed moderate to high volatile matter: coconut fruit bunch (CFB) 75.2%, groundnut shell (GNS) 73.9%, coconut shell (CS) 73.9%, and palm kernel fruit bunch (PKFB) 73.5%.

The differences in volatile matter content are primarily linked to the lignocellulosic composition of raw biomass. Materials with higher hemicellulose and cellulose fractions generally exhibit higher volatile matter, whereas high-lignin shell materials may vary depending on processing (Anuchi *et al*., 2022; Anwar *et al*., 2014). The generally high volatile matter (over 69%) across all samples suggests good ignition properties suitable for thermochemical conversion processes. These experimental results align closely with those of Jagtap & Kalbande. (2023) and Erokare *et al*. (2025), who reported volatile matter contents for biomass pellets typically ranging from 65% to 85%, with agricultural residues and woody materials often falling in the upper range. Umubigho *et al*. (2025) and Ighodaro *et al*. (2023) confirm high volatile matter in sawdust and palm kernel shell pellets. Bazargan *et al*. (2020) and Ezeokolie *et al*. (2024) further validate the relatively lower volatile matter in rice husk, attributed to its high ash and silica content.

In conclusion, the volatile matter contents observed in this study indicate that all biomass types possess favourable combustion characteristics. Sawdust, palm kernel shell, and sugarcane bagasse pellets stand out for their particularly high volatile matter content, making them promising candidates for rapid ignition and efficient energy recovery. The data support the use of these agro-industrial residues as sustainable solid biofuels, provided that other parameters, such as ash content, are appropriately managed.

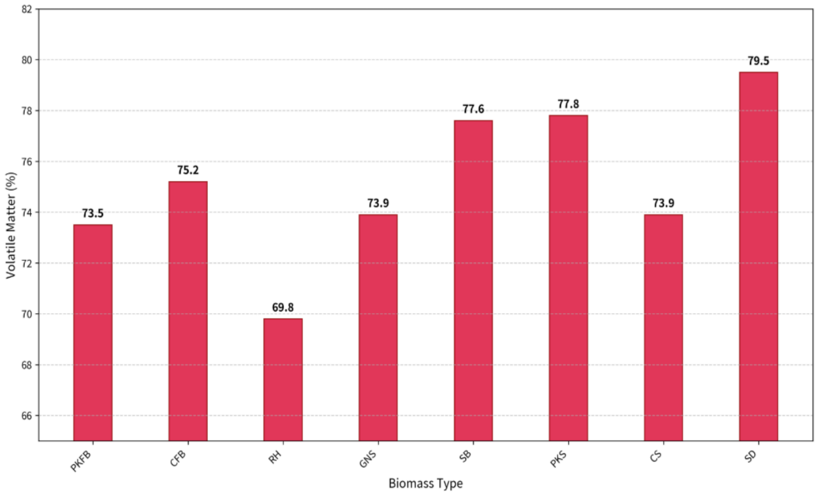

Figure 3: Volatile Matter of Various Biomass Types

Ash Content (%) Analysis

The ash content of the eight pelletized biomass samples, as determined experimentally and presented in Table 2 alongside Figure 4, ranged from 1.1% (sawdust) to 18.5% (rice husk). Ash content is a key quality parameter for biomass fuels because it significantly influences combustion behaviour, boiler performance, and operational costs. Sawdust (SD) exhibited the lowest ash content at 1.1%, followed by coconut shell (CS) at 1.9% and palm kernel shell (PKS) at 2.4%. These low values indicate excellent fuel quality with minimal inorganic residue. Moderate ash contents were recorded for coconut fruit bunch (CFB) at 4.3%, sugarcane bagasse (SB) at 4.8%, and groundnut shell (GNS) at 5.7%. In contrast, palm kernel fruit bunch (PKFB) showed 8.8% ash, while rice husk (RH) recorded a markedly high ash content of 18.5%.

High ash content, particularly in rice husk, is primarily attributed to its elevated silica concentration, which is typical of many agricultural residues. The results reveal a clear inverse relationship between ash content and calorific value: samples with lower ash (such as SD, CS, and PKS) generally demonstrated higher energy density. This relationship is consistent with fundamental thermochemical principles, in which inorganic ash dilutes the combustible organic fraction, thereby reducing the overall heating value. (Onochie *et al*., 2025; Jekayinfa *et al*., 2020).

These findings align with those of Jekayinfa *et al*. (2020) and Yao *et al*. (2017), highlighting the operational challenges associated with high-ash biomass, including slagging, fouling, and increased particulate emissions. Lachman *et al*. (2021) and Chen *et al*. (2021) studies emphasize the advantages of low-ash pellets for efficient combustion and reduced maintenance. Yang *et al*. (2025), Nikdalila *et al*. (2020). Research further confirms the exceptionally high ash content in rice husk pellets and its negative impact on fuel performance. Ash content is a critical determinant of biomass pellet quality. Sawdust, coconut shell, and palm kernel shell pellets exhibit superior characteristics, with low ash content, making them highly suitable for clean, efficient bioenergy applications. High-ash materials such as rice husk may require pre-treatment (e.g., leaching or blending) or be better suited for alternative valorization pathways. The results underscore the importance of strategic feedstock selection for developing high-quality biomass pellets for sustainable energy production.

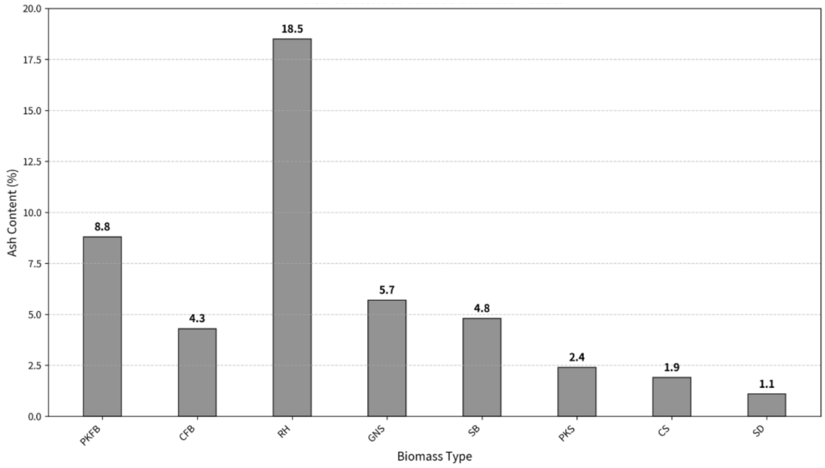

Figure 4: Ash Content of Various Biomass Types

Fixed Carbon (%) Analysis

The fixed carbon content of the eight pelletized biomass samples, as determined experimentally and presented in Table 2 alongside the corresponding graph (Figure 5), ranged from 11.7% (rice husk) to 20.8% (coconut shell). Fixed carbon, which remains after devolatilization, plays a crucial role in the char combustion phase and in overall energy release during biomass thermal conversion. Coconut shell (CS) exhibited the highest fixed carbon content at 20.8%, followed by palm kernel shell (PKS) at 18.2% and groundnut shell (GNS) at 15.8%. Moderate values were recorded for coconut fruit bunch (CFB) at 15.1%, sawdust (SD) at 15.7%, sugarcane bagasse (SB) at 13.9%, and palm kernel fruit bunch (PKFB) at 13.8%. Rice husk (RH) showed the lowest fixed carbon content at 11.7%. Higher fixed carbon levels prolong char combustion, providing sustained heat output and improved burnout characteristics. Consequently, coconut shell and palm kernel shell pellets are expected to demonstrate superior combustion efficiency and stability. In contrast, the lower fixed carbon in rice husk may result in faster burnout and greater dependence on volatile combustion, potentially leading to lower overall thermal efficiency, especially when combined with its high ash content.

The results reveal a positive correlation between fixed carbon content and calorific value across the samples. This relationship is consistent with fundamental thermochemical principles, in which inorganic ash dilutes the combustible organic fraction and reduces the overall heating value, while fixed carbon contributes substantially to the energy released during the char oxidation stage (Bazargan *et al*., 2020; Ezeokolie *et al*., 2024). These findings are supported by Jekayinfa *et al*. (2020) and Yao *et al*. (2017), stating the importance of high fixed carbon for stable combustion and high energy recovery in biomass pellets. Onochie *et al*. (2025) and Ighodaro *et al*. (2023) further confirm that materials with elevated fixed carbon content generally exhibit better combustion performance. Fixed carbon content is a key indicator of combustion efficiency in biomass pellets. Coconut shell and palm kernel shell are the most promising feedstocks due to their high fixed carbon content. For lower-performing materials such as rice husk, blending or advanced pre-treatment may be necessary to enhance fuel quality. The results emphasize the value of comprehensive proximate analysis in selecting and optimizing biomass resources for sustainable bioenergy applications.

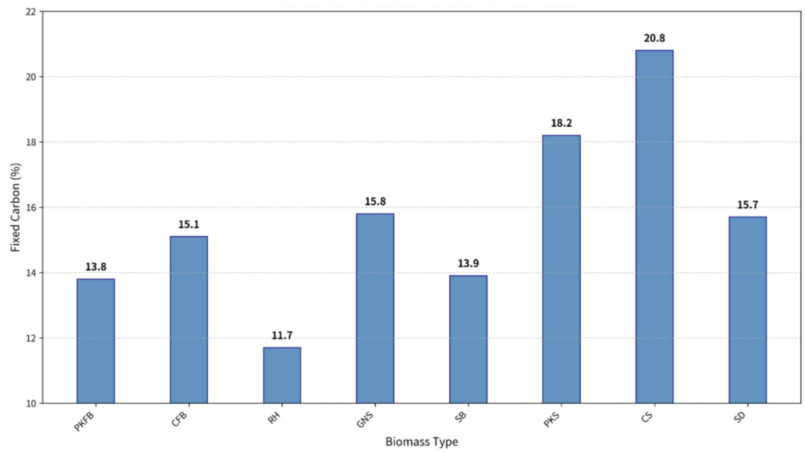

Figure 5: Fixed Carbon of Various Biomass Types

CONCLUSION

This study evaluated the calorific value and proximate composition of pellets produced from eight different agricultural biomass wastes: palm kernel fruit bunch (PKFB), coconut fruit bunch (CFB), rice husk (RH), groundnut shell (GNS), sugarcane bagasse (SB), palm kernel shell (PKS), coconut shell (CS), and sawdust (SD). The experimental results demonstrated significant variations in fuel properties among the samples. Palm kernel shell (PKS) and coconut shell (CS) pellets exhibited the highest calorific values (20.1 MJ/kg and 19.6 MJ/kg, respectively), coupled with low ash content (2.4% and 1.9%) and high fixed carbon (18.2% and

20.8%). These characteristics make them the most promising feedstocks for high-efficiency bioenergy applications. In contrast, rice husk pellets had the lowest calorific value (15.3 MJ/kg) due to an exceptionally high ash content (18.5%), highlighting the need for pre-treatment or blending to improve their fuel quality.
All samples maintained acceptable moisture levels (below 12%), with sawdust recording the lowest at 7.9%. Volatile matter content was generally high (over 69%), indicating good ignition properties across the board. The positive correlation between fixed carbon content and calorific value, along with the inverse relationship with ash content, aligns with fundamental thermochemical principles and underscores the importance of comprehensive proximate analysis in selecting biomass feedstocks. The findings confirm that locally available agricultural residues, particularly palm kernel shell and coconut shell, possess excellent potential as sustainable solid biofuels. Their superior energy density and favourable combustion characteristics support their utilization in pellet form for heat and power generation. This research contributes to the valorization of agro-industrial waste, promoting circular-economy principles and renewable-energy development in biomass-rich regions.

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