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Characterization of Cashew Nutshell Residue for Energy Application

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Abstract **Review Article**

Cashew nutshell residue constitute about 35-50 % of the total weight of the cashew fruit depending on the species. The nutshell is typically discarded through burning or left to decompose, leading to environmental pollution and wasted potential resources. This research aims to contribute to sustainable waste management practices, reduce environmental pollution from agricultural residues and explore new avenues for renewable energy sources and applications.

The CNS was collected from Global Confluence Nigeria Limited Odo-Omu, Area, Iseyin, Oyo State, Nigeria. The collected samples were manually decorticated, cleaned and sorted to separate immature shells, stalks, leaves and other impurities from the shells. Thereafter, the cleaned CNS was sun dried for 10 days to reduce the moisture content of the residues to safe storage level of about 10 - 12 % dry basis. The cleaned and sun dried CNS was also milled and sieved into 2 mm sample sizes for further studies. The ground sample was collected for characterization of their proximate compositions analysis of moisture content, volatile matter, ash content and fixed carbon content, ultimate compositions analysis of H, C, O, N and heating values and structural compositions of cellulose, hemi-cellulose and lignin contents following the American Standard for Testing and Material, ASTM E872-82 and ASTM D1102-84.34 standards.

The study revealed proximate, ultimate, energy and structural compositions of CNS. The moisture, ash, volatile matter, fixed carbon and dry matter contents for cashew nutshell were 11.12, 2.5, 65.23, 28.14 and 89.88 % while C, O, H, N, S and energy content were 45.13, 45.79, 5.12, 1.25, 0.20 % and 14.29 MJ/kg while structural composition was 14.78, 25.19 and 29.65 % for hemicellulose, lignin and cellulose, respectively. This study emphasizes the promise of CNS as a better feedstock for bioenergy production with environmental and economic benefits in terms of promoting sustainable waste management practices and explore new avenues for renewable energy applications.

Keywords: Cashew nutshell, proximate, ultimate, energy, structural compositions, ASTM standards.

Introduction

The constant growing on global population is driving increased demand for energy, food and agricultural production. The food and agricultural production lead to a significant upsurge in the production of biomass residues.

This rampant production not only poses environmental challenges but also escalates the costs associated with residues disposal. Agriculture, as one of the most widespread human activities, generates surplus crop residues year-round, a substantial portion of which often goes to waste (Prasad *et al.*, 2020). The Food and Agriculture Organization (FAO) estimates global agricultural residues at around 10 – 12 billion tonnes per year including crop residues like straw, stover, husks etc. (FAO, 2023). The management of these residues is a major concern in today's society as most residues are been burnt, chemically treated, dumped into waterways or buried in landfills. Forty percent of garbage is simply dumped with no further processing (FAO, 2023). Poor residue disposal is hazardous to people's health and the environment because it pollutes the air, water and soil and facilitates disease transmission (Kosre *et al.*, 2021).

The disposal of CNR through burning contributes to air pollution by releasing greenhouse gases and particulate matter into the atmosphere (Nwachukwu and Ude, 2014). This not only poses environmental hazards but also represents a missed opportunity for utilizing CNR as valuable resources.

However, specific research on cashew nutshell residue pyrolysis remains limited, highlighting a significant gap in current knowledge. Understanding the chemical composition of cashew nutshell residues is crucial for optimizing the potential of CNS for bioenergy applications. This study seeks to address these gaps by exploring the potential of cashew nutshells residues as a feedstock for renewable energy source to contribute to sustainable waste management practices and reduce environmental pollution from agricultural residues.

Materials and Methods

Sample Preparation

The cashew nutshells were collected from Global Confluence Nigeria Limited, Odo-Omu, Area, Iseyin, Oyo State, Nigeria with a geographical location (7.9765^{o} North, 3.5914^{o} East). The collected cashew nutshells were manually cleaned and sorted to separate immature shells, stalks, leaves and other impurities from the shells as shown in Plate 1a. There after the cleaned shells were sun dried for about 7 to 10 days to reduce the moisture content of the shells to safe storage level of about 10 - 12 % moisture content. The cleaned and sun dried cashew nutshells, Plate 1a, were then milled and sieved into 2 mm sample sizes, Plate 1b, for the pyrolysis process. The ground cashew nutshell sample was then weighed and packaged and for the pyrolysis process.

(a) (b)

Plate 1: Samples: (a) Cleaned and sun dried cashew nutshells; (b) Milled cashew nutshells

Characterization of Cashew Nutshell

The ground sample was collected for characterization of their proximate compositions analysis of moisture content, volatile matter, ash content and fixed carbon content, ultimate compositions analysis of H, C, O, N and heating values and structural compositions of cellulose, hemi-cellulose and lignin contents following the American Standard for Testing and Material, ASTM E872-82 and ASTM D1102-84.34 standards as described by Kumar *et al.* (2020).

Moisture content determination

Moisture content of the sample was determined using the oven drying procedure of the ASTM E871-80 standard method. Sample weights of about 10 g of the sample was oven dried at a temperature of 105 °C until a constant weight of the dried sample is obtained. The data obtained in three replicates from the weights measurement of the sample before and after drying were used to calculate the percentage of moisture content of the sample using Equation 1.

$$MC_{db\ or\ wb} = \frac{A-B}{A} \times 100 \qquad 1$$

Where:

MC = moisture content (%)

A= Weight of the sample before drying (g)

B = Weight of dry sample after drying (g).

Ash content determination

The ASTM E1755- II (2017) standard was used to analyze the ash content of the sample. The crucible for the analysis was pre-heated in a muffle furnace at 750 °C, then cooled and weighed. Thereafter a weighted 5 g of the sample was placed in the pre-heated crucible. The crucible with the weighed sample was placed in the muffle furnace and heated at 750 °C temperature for 6 h. After the combustion, the crucible was removed and cooled in a desiccator and weighed again to determine the remaining ash. The data obtained from replicates of the experiment was used to calculate the percentage ash content of the samples using Equation 2.

$$Ash = \frac{X}{Y}\, x\ 100 \qquad 2$$

Where:

Ash = Ash Content (%)

X = Weight of ash after combustion (g)

Y = Weight of the sample (g).

Volatile matter content determination

The volatile matter content was obtained by the ASTM D3172-13 (2017) standard method. A weighted sample of 2 g was pulverized in a porcelain and oven dried to a constant weight at 105 °C temperature. The dried sample with porcelain was then kept in a furnace at a temperature of 550 °C for 10 minutes and weighed again after cooling in a desiccator. The percentage volatile matter was calculated using Equation 3.

$$VM = \frac{B-C}{B}\, x\ 100 \qquad 3$$

Where:

VM = Volatile Matter (%)

B = Initial mass of the sample (g)

C = Final mass of sample (g).

Fixed carbon content determination

In obtaining the fixed carbon, ASTM D3174 – 76 (2017) standard method was used. The crucible cover used in performing the volatile matter last analysis was removed after which the crucible heated over Bunsen burner to allow all the carbon to burn. The difference in weight of the residue from the previous weight is the fixed carbon and was calculated using Equation 4.

$$FFC = 100 - (MC + VM + ASH) \qquad 4$$

Where:

FFC = Fixed carbon content (%)

MC = Moisture content (%)

VM = Volatile matter content (%)

ASH = Ash content (%).

Carbon content determination

The percentage of the carbon (C) was determined using (ASTM D3178) standard method, (2017) by adopting Equation 5.

$$C = \frac{(B-T)\ x\ M\ x\ 0.003\ x\ 100\ x\ 1.33}{Ws}\ x\ 100 \qquad 5$$

Where:

C = Percentage of carbon content (%)

B = Blank titer (g)

T = Sample titer (g)

M = Molarity of the acid that will be used (mol/L)

W_s = Weight of the sample (g).

Nitrogen content

The percentage of nitrogen (PN) was determined using ASTM D3179 standard method, (2017) using Equation 6.

$$N = \frac{T\ x\ M\ \ x\ \ 0.014\ \ x\ \ DF}{Ws}\ x\ 100 \qquad 6$$

Where:

M = Molarity of the acid used ((mol/L)

W_s = Weight of the sample (g)

T = Titre value (mL)

DF = Dillusion factor.

Sulphur content

The percentage of sulphur (S) was determined using ASTM D3177 standard method, (2017) by using Equation 7.

$$S = \frac{X\ x\ 0.1373}{Ws}\ x\ 100 \qquad 7$$

Where:

S = Sulphur content (%)

W_s = Weight of the sample (g)

X = Weight of $BaSO_4$..

Hydrogen content

The percentage of hydrogen (H) was determined using ASTM D3178 standard method (2017) by using Equation 8.

$$H = \frac{Ww\ x\ \ 0.119}{Ws}\ x\ 100 \qquad 8$$

Where:

W_w = Weight of water (g)

W_s = Weight of sample (g).

Oxygen content

The percentage of oxygen (O) was determined by difference according to Pedro *et al.*, (2018) using Equation 9.

$$O = 100 - (C + H + N + S + \ \%ASH) \qquad 9$$

Where:

C = Carbon content (%)

H = Hydrogen content (%)

N = Nitrogen content (%)

S = Sulphur content (%)

ASH = Ash content (%).

Calorific value

The calorific value of the samples was determined using bomb calorimeter in accordance with ASTM D5865-13 (2017) standard method. The high and low calorific values which was calculated by using the dulong formula as given by Equations 10 and 11.

$$HCV = 4.18\ x\ (78\ x\ C + 241.3\ x\ \ \frac{H\ x\ O}{8} + \ 22.1\ \text{x S} \qquad \mathbf{10}$$

$$LCV = 4.18\ x\ (94.19\ x\ C - 0.550 - 52.14\ x\ H) \qquad \mathbf{11}$$

Where:

HCV = Higher calorific value, (MJ/kg)

LCV = Lower calorific value, (MJ/kg)

C = Percentage of carbon content (%)

H = Percentage of hydrogen content (%)

O = Percentage of oxygen content (%).

Hemicellulose content in the samples

In obtaining hemicellulose in biomass. 1 g of the biomass sample was weighed (W_3) into a flask. 10 mL 2N H_2SO_4 was added (autoclave, 121 °C, 1 hr), filter and wash and the filtrate collected (100 mL). Reducing sugars was determined using (DNS method, glucose standard). Hemicellulose was determined as sugars (g) × 0.88 AOAC International, (2016). The amount of hemicellulose was calculated by using Equation 12.

$$\text{Hemicellulose (\%)} = \frac{Reducing\ sugars\ (g)x\ 0.88}{W3} \quad 12$$

Lignin content in the samples

In determining the content of lignin in biomass. 1 g of the sample was weighed (W_4) into a flask. About 15 mL 72 % H_2SO_4 was added (30 °C, 2 hr, stir occasionally) and diluted to 4 % H_2SO_4 (autoclave, 121 °C, 1 hr). The mixture was filtered through crucible, washed and dry residue (105 °C, 2 hr). The residue was weighed (W_5) as acid-insoluble lignin AOAC International, (2016). The final weight of residue was recorded as lignin content using Equation 13.

$$\text{Lignin (\%)} = \frac{W5}{W4}\ x\ 100 \quad 13$$

3.3.13 Cellulose content in the samples

The sample was grinded to a fine powder (<1 mm), dried in an oven (105 °C, 24 hr) and stored in airtight containers. Using Acetic-Nitric Acid Method. 1 g of the sample was weighed (W_1) into a flask. 3 mL acetic acid + 1 mL nitric acid was added (reflux, 30 min) and filtered through Whatman No. 1 paper, washed with water and dried with (105 °C, 2 hr). The residue was weighed (W_2) as cellulose AOAC International, (2016). The content of cellulose (E) was determined using Equation 14.

$$\text{Cellulose (\%)} = \frac{W2}{W1}\ x\ 100 \quad 14$$

Result and Discussions

Proximate and Ultimate Compositions of Cashew Nutshell

The results obtained for the proximate (moisture, ash, volatile matter, fixed carbon, dry matter contents) and ultimate (carbon, oxygen, nitrogen, sulphur and energy contents) analysis of cashew nutshells are presented in this section.

Result of proximate compositions of raw cashew nutshells and velvet bean pod

Table 1 presents the proximate composition of cashew nutshells. This highlighting key parameters such as moisture, ash, volatile matter, fixed carbon and dry matter content. This data is essential for evaluating it potential as biomass feedstocks for energy applications (combustion, gasification, and pyrolysis), soil amendments or even for biochar production.

The moisture content for the cashew nutshells is 11.12 %. The lower moisture content is generally preferred in biomass fuels because it reduces energy loss during combustion (less energy is spent evaporating water). Moisture content is critical for storage, handling and thermal conversion efficiency. According to Demirbaş (2004), optimal moisture for solid biofuels is typically <10 – 15 %. Cashew nutshell moisture values reported elsewhere range from 7.3% to 13.5 % depending on drying conditions and origin (Adeyemi and Olorunnisola, 2014; Adeniyi *et al.*, 2018). The 11.12 % obtained as shown in Table 4.1 is slightly higher but still within acceptable limits for biomass feedstocks.

The ash content for cashew nutshells is 2.51%. Ash represents the inorganic, non-combustible fraction. Cashew nutshells have lower ash content, which is advantageous for thermochemical conversion processes, as high as content can cause slagging, fouling and reduced efficiency. Ash content reflects inorganic residue after combustion. Low ash (< 5 %) is desirable for clean combustion and gasification. Cashew nutshell ash values according to (Adeniyi *et al.*, 2018) range from 1.2 to 3.0 %, making the 2.51 % obtained in Table 4.1 consistent.

The volatile matter content for cashew nutshells is 65.23 %. Volatile matter consists of gases and vapors released during heating. High volatile matter aids in ignition and flame stability but may reduce char yield. Cashew nutshells, with higher volatile matter, are likely more reactive during pyrolysis or combustion, making them suitable for gasification or fast pyrolysis to produce bio-oil. High volatile matter (> 60 %) usually indicates good reactivity during pyrolysis or combustion. Cashew nutshell is typically reported with 65 – 75 % volatile matter (Adeniyi *et al.*, 2018). The 65.23 % volatile matters in Table 4.1 falls within the typical values for cashew nutshells.

The fixed carbon content for cashew nutshells and velvet bean pod is 20.14 %. Fixed carbon reflects the solid combustible residue after volatile matter is driven off. Typical cashew nutshell fixed carbon falls between 15 – 22 % (Adeniyi *et al.*, 2018). The 28.14 % is high, possibly due to lower volatile matter (as fixed carbon and volatile matter are inversely related).

The dry matter for cashew nutshells is 89.88 %. Dry matter content complements moisture results. Cashew nutshell has higher dry matter, confirming it lower water content and potentially better storage stability. The sample meet the minimum dry matter requirement (≥ 85 %) for solid biofuels per ISO 17225-6, ensuring acceptable energy density and storage stability.

Table 1: Proximate Compositions of the Cashew Nutshell

Residue	**Properties**	**Proximate Value, %**
Cashew Nutshell	Moisture Content	11.12
	Ash Content	2.51
	Volatile Matter	65.23
	Fixed Carbon Content	28.14
	Dry Matter	89.88

Results of ultimate compositions of cashew nutshell

The results obtained for the ultimate composition analysis and higher/lower heating values (HHV/LHV) of the cashew nutshell are as presented in Table 2. Ultimate analysis results showed that cashew nutshells has 45.13 % C, 5.12 % H, 1.25 % N, 45.79 % O and 0.20 % S also 10.49 MJ/kg HHV and 9.46 MJ/kg LHV. These elements constitute the major compositions of cashew nutshells as this is evident from the results of elemental composition in Table 2. This provides critical insights into the chemical energy potential, combustion behavior, emission characteristics and suitability for thermochemical conversion (e.g., pyrolysis, gasification, combustion).

The carbon content for cashew nutshell is 45.13 %. Carbon is the primary contributor to the energy content of biomass. Higher carbon generally correlates with higher heating value. Typical biomass carbon content ranges from 40 – 50 % (dry ash-free basis) (Demirbaş, 2004). The carbon content of 45.13 % for the cashew nutshells in this study falls within carbon content ranges from 45 – 52 % for cashew nutshells reported by (Adeniyi *et al.*, 2018).

The hydrogen content for cashew nutshell is 5.12 %. Hydrogen contributes significantly to HHV (via water formation during combustion). Typical hydrogen in biomass falls between 5 – 6 % (Dry Ash-Free, DAF) as reported by Vassilev, *et al.* (2010). The hydrogen content of 5.12 % for the cashew nutshell in this study was lower than hydrogen content 6.1 % for cashew nutshells reported by (Shrirame *et al.*, 2021) and also slightly falls below 5.5 – 6.5 DAF cashew nutshell range.

The nitrogen content for cashew nutshell is 1.25 %. The higher the nitrogen content the higher the producer gas and vice versa. The nitrogen content of 1.25 % for the cashew nutshells in this study falls within 1.2 - 2.0 % as reported for cashew nutshells by (Adeniyi *et al.*, 2018) but higher than 0.1 – 1.0 % for typical biomass materials.

The oxygen content for cashew nutshells is 45.79 %. Oxygen content shows how combustible the sample is, high level of oxygen indicate that the material is having high combustible indicator and vice versa. The oxygen content of 45.79 % for the cashew nutshell in this study was slightly higher than 35 – 45 % range as reported by Bridgwater, 2012 for typical biomass materials.

The sulphur content for cashew nutshells is 0.20 %. Sulphur content indicates how poisonous is the sample as the content can easily reacts with oxygen content to form and release sulphur (IV) oxide gas which is dangerous to human beings. The higher the sulphur content, the higher the poisons releases to the environment. The sulphur content of 0.20 % for the cashew nutshell in this study was higher than the range of 0.02 – 0.10 % reported for typical biomass materials by Vassilev *et al.* (2020). Sulphur leads to SO_2 emissions, causing acid rain, equipment corrosion and catalyst poisoning in gasification systems.

Table 2: Ultimate Compositions of Cashew Nutshell

Residue	**Properties**	**Ultimate Value, %**
Cashew Nutshell	Carbon Content	45.13
	Hydrogen Content	5.12
	Nitrogen Content	1.25
	Oxygen Content	45.79
	Sulphur Content	0.20
	Higher Heating Value (MJ/kg)	14.29
	Lower Heating Value (MJ/kg)	12.81

The Higher Heating Value (HHV) for cashew nutshells is 14.29 MJ/kg, respectively. 14.29 MJ/kg (cashew nutshell) falls within the typical range for raw agricultural residues. The Higher Heating Value (HHV) quantifies the total thermal energy released during complete combustion, including condensation of water vapor. For biomass, HHV typically ranges from 14 – 20 MJ/kg on a dry basis, depending on composition (Demirbaş, 2004). The value of 14.29 MJ/kg is at the lower end of reported cashew nutshell HHVs and also lower than the findings by Shrirame *et al.* (2021), who obtained cashew nutshells value of 15.8 MJ/kg HHV. Cashew nutshell remains a moderate-energy and high-availability residue.

The Lower Heating Value (LHV) for cashew nutshells is 12.81 MJ/kg. The Lower Heating Value (LHV) represents the usable energy from biomass combustion excluding the latent heat of vaporization of water produced during hydrogen combustion. 12.81 MJ/kg (cashew nutshell) falls within the typical range for raw agricultural residues of 12.5 – 14.5 MJ/kg. The value of 12.81 MJ/kg is lower than 13.5 – 15.0 MJ/kg LHV obtained for cashew nutshells by Adeniyi e*t al.* (2018). Cashew nutshell compensates with abundance and thermochemical versatility also exemplify how underutilized agro-residues can contribute to energy access, waste reduction, and circular agriculture.

Results of lignocellulosic compositions of cashew nutshell

The results obtained for the lignocellulosic compositions (hemicellulose, lignin and cellulose) of the cashew nutshells are as presented in Table 3. The lignocellulosic composition results showed that cashew nutshells has 14.78 % hemicellulose, 25.19 % lignin and 29.65 % cellulose. These elements constitute the major lignocellulosic compositions of cashew nutshells and velvet bean pod. Lignocellulosic biomass consists of three primary polymeric components, cellulose, hemicellulose and lignin. High cellulose favorable for bioethanol, nanocellulose or chemical pulping. High lignin is suitable for biochar, activated carbon or aromatic chemical recovery. High hemicellulose beneficial for furfural/xylan production but can cause inhibitor formation in fermentation.

The value obtained for hemicellulose for cashew nutshell is 14.78 % which falls within 12.5 – 16.0 % as reported by Adeniyi *et al.*, 2018. The hemicellulose suggests high lignification or sample maturity. Most agro-residues contain 20 – 30 % hemicellulose (Saha, 2003). The low value here aligns with cashew nutshell's resinous, protective biological function. This is notably low compared to herbaceous biomass (typically 20 – 35 %). This value obtained may be due to high maturity at harvest, substitution by non-carbohydrate polymers or interference from extractives during hydrolysis.

Table 3: Structural Compositions of Cashew Nutshell and Velvet Bean Pod

Residue	Properties	Structural Value, %
Cashew Nutshell	Hemicellulose	14.78
	Lignin	25.19
	Cellulose	29.65

The value obtained for lignin for cashew nutshell is 25.19 % which falls within 12 – 27.5 % as reported by Adeniyi *et al.* (2018). This is higher than 18 % which was reported by Sun and Cheng (2002) for rice husk. Lignin-rich feedstocks produce high biochar yields (30 – 40 %) and phenolic bio-oils (Mohan *et al.*, 2006).

The value obtained for cellulose is 29.65 %. This value is lower than typical lignocellulosic feedstocks, Hardwoods (40 – 50 %) cellulose and agricultural residues (32 – 40 %) Sun and Cheng, (2002). The value obtained for celullose of cashew nutshell is 29.65 % which falls within 28.4 – 32.1 % as reported by Adeniyi *et al.*, 2018. However, cashew nutshell is not a typical fiber-rich residue; it is a byproduct of nut processing, rich in anacardic acids and phenolic lipids, which may dilute polysaccharide content or interfere with cellulose quantification.

Conclusion

Cashew nutshell has been characterized. The moisture, ash, volatile matter, fixed carbon and dry matter contents for cashew nutshell are 11.12, 2.5, 65.23, 28.14 and 89.88 % while C, O, H, N, S and energy content were 45.13, 45.79, 5.12, 1.25, 0.20 % and 14.29 MJ/kg while structural composition are 14.78, 25.19 and 29.65 % for hemicellulose, lignin and cellulose, respectively. This study emphasizes the promise of CNS as a better feedstock for bioenergy production with environmental and economic benefits in terms of promoting sustainable waste management practices and explore new avenues for renewable energy sources and applications.

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