EVALUATION AND ANALYSIS OF DIVERSE BIOMASS FEEDSTOCKS FOR SUSTAINABLE BIOENERGY PRODUCTION IN NORTHERN NIGERIA

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ABSTRACT

Energy is one of the necessary resources in the world, and developing countries like Nigeria are struggling to meet the continuous energy demand. As a result of farming practices and the population in Northern Nigeria, a high amount of lignocellulosic and carbonaceous biomass is produced as a waste material. However, countless types of biomasses, such as fruit, vegetable, bagasse, strain, and municipal waste, are selected based on availability and characterised to check their energy production potential. The samples were prepared by cyclone milling to 2 mm. Sieve analysis through sieves of size 2.36 mm, 2.00 mm, 1.18 mm, 900 µm, and 850 µm was used to obtain the distribution of particle size with passing ranging from 60.75% to 86.80%, 47.93% to 73.95%, 12.64% to 40.54%, 11.45% to 27.46%, and 8.55% to 22.61%, respectively. Proximate analysis was conducted and compared across the materials, including total solids, moisture content, volatile content, ash content in percentage of the individual samples, and density in g/ml. Calorific values of the energy contents of the materials were obtained and compared across the materials, with a maximum value (17.64 MJ/kg) for vegetable waste and a minimum value of (8.24 MJ/kg) for maise corn stove and sorghum corn stover. Fibre content analysis was conducted; the materials' lignin cellulose and hemicellulose contents were evaluated and compared. The studies indicate the feasibility of generating biogas from biomass through anaerobic digestion.

Keywords: *anaerobic digestion, biogas, biomass, energy demand, lignocellulosic, Northern Nigeria.*

INTRODUCTION

Energy has been essential for all living organisms for centuries and is responsible for sustaining the ecosystem and life on Earth. Energy production and consumption are critical global economic growth and sustainability drivers [1]. The global energy crisis and global warming threats have made it necessary to divert from the utilisation of fossil fuels [2]. It has been realised that a lack of alternative energy means would result in endless energy shortages; hence, the environment will continue to be at risk. Another challenge is poor waste management, which leads to environmental pollution [3]-[4]. It is presumed that 2.2 billion metric tons of municipal solid waste will be produced next year on Earth, management of which is difficult in Nigeria despite the government and private efforts; this results from the growth of many Nigerian cities [5]. In the total primary energy supply, the share of renewable energy will rise from 14% in 2015 to 63%, where bioenergy from biomass resources alone will take approximately two-thirds in 2050 [6]. In Nigeria, the available biomass resources include grasses, trees, residues, aquatic waste, agricultural waste, municipal waste, and industrial waste [7], which can sum up to 144 million tons per annum [8].

Lignocellulosic biomass is primarily generated (about 181.5 billion tons yearly worldwide). It is common in Northern Nigerian (Figure 1) because of a high number of farming practices. They are known as energy crops for their high dry matter yields, durability, and low production costs. They can be purposely planted for energy generation [9] and produced in enormous quantities for consumption procession and exportation, and hence they generate a considerable amount of residues [10]; the residues, better called agricultural wastes produced as a result of storage limitations or processing of crops include stalks, shells, straws, cobs, husks, hulls, peels, barks, and effluents which can be used as building materials and animal fodders [11] and could father be utilised to produce about 21 billion cubic meters of biogas according to the report. Despite the increase in the biogas industry worldwide, the Energy potential of these agricultural wastes has not yet been exploited [10].

Municipal wastes are a non-homogeneous mixture of residential, industrial, and commercial wastes [12]. The solid waste generation rate depends on the peculiar characteristics of the city [13], and so does the composition of the waste in Nigeria, as compiled in different studies. The organic constituents of municipal waste contribute the highest proportion, accounting for 78% of the total waste composition [14]. As a result, municipal waste can be effectively utilised for energy production through incineration or anaerobic degradation to generate methane. However, to fully

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harness the energy potential of municipal solid waste, it is essential to conduct a thorough analysis of its energy capabilities. Moreover, the successful exploitation of this potential is contingent upon the implementation of proper waste management practices.

The first step in comprehending and characterising the bioenergy of carbonation biomass is through the bioenergy potential estimation of the materials [15]. The quantitative characterisation can be categorised as proximate and ultimate analysis; the proximate analysis consists of total solids, volatile solids, moisture contents, and calorific value estimations; the ultimate analysis involves elemental analysis (C, H, N, S) [16]. The energy contained in biomass can be estimated using the higher heating value (HHV) and lower heating value (LHV), which are essential for calculating energy potential in biomass.

Northern Nigeria uses most of its agricultural practices, as shown in Figure 1, producing the highest amount of carbonaceous biomass as agricultural and municipal waste. Therefore, this paper aims to evaluate and analyse diverse biomass feedstocks for sustainable bioenergy production in Northern Nigeria.

Figure 1 Northern Nigeria as a significant source of lignocellulosic biomass [17]

MATERIALS AND METHODS

Sample Collection

All the collection and preservation programs were by the Waste Management Standard ASTM D5231-92 [18]. The samples include solid samples, namely, fruit wastes (watermelon and banana peels, and orange peels) obtained from the fruit market refuse damping area; vegetable wastes obtained from residential waste dumping area; bagasse (sugarcane bagasse, rotten sugarcane bagasse) obtained from farms and sugarcane markets; stover (sugarcane stover, maise corn stover, sorghum corn stover, and millet corn stover) obtained from farms; rice straw obtained from the farm; and municipal waste obtained from municipal waste dumping areas. The sources are shown in Figure 2.

Figure 2 Lignocellulosic biomass sample collection sources: (a, b) fruit market, (c, f) sugarcane market (d) abattoir, (e) farm products storage, and (g, i) municipal waste dumping area (h) sugarcane waste dumping area

Figure 2 shows the biomass sample sources, including municipal waste dumping areas, farm products storage, markets, and abattoirs. Uniform replicate samples were collected to determine the physical and chemical composition of the sample.

Sample Preparation

The solid samples were air dried and then homogenised and reduced in the cyclone cutting mill, sieved through a 2.00 mm sieve; the retained sample was further broken and sieved again to achieve particle reduction, regimentation of the organic matter and nutrient content, and to achieve proper workability. During the research, personal protective equipment (PPE) was required to minimise exposure to occupational hazards. PPE required included safety gloves, safety nose masks, overalls, and protective shoes.

Particle Size Distribution

The particle size took place in steps. Sieves of size 2.36 mm, 2.00 mm, 1.18 mm, 900 µm, 850 µm, and the pan were set accordingly (as shown in Figure 2c), the samples of known weights were sieved in duplicates, and the retained samples were weighed. The mass retained in the sieves and the pan were measured, recorded as $m_{retained}$, and added up to obtain the total mass m_{total} in both cases. The percentage (by mass) retained on each sieve was determined and subtracted from the percentage passing through the previous one; this was recorded as the percentage passing through the current sieve. Percentage retained (*%Retained*) and percentage passing (*%Passing*) were calculated as:

$$\%Passing\ sieve\ y = \left(\frac{m_{retained}\ on\ sieve\ y}{m_{total}}\right)\times 100 \quad (1)$$

$$\%\ Retained\ on\ sieve\ y = \%Passing\ x - \%Passing\ y \quad (2)$$

Colour and Odour Assessment

Appropriate PPE, such as gloves and masks, were worn during the colour and odour assessment. The assessment was conducted per ISO 13301 [19], general guidance for measuring odour, flavour, and taste detection thresholds by a three-alternative forced-choice (3-AFC) procedure. The samples of adequate size were collected and spread uniformly on a clean, flat surface with a white background for a neutral contrast. The samples were visually inspected under natural light. The predominant and noticeable colours of the samples with multiple colours were identified and noted following the colour guide.

The samples were placed in an open container and allowed to sit for 60 seconds. The container was held at a distance ≥ 300 mm from the nose, and the air was wafted towards the nose above the sample; the odours were identified and described using common descriptors, and complex odours were broken down into primary and secondary notes. Three individuals assessed the samples independently.

Proximate Analysis

Proximate analysis is shown in Figures 3a and 3d. For total solids and moisture contents, the empty dish was evaporated at 550°C for 1 hour. The dish was allowed to cool to 100°C in the oven, desiccated to room temperature, and weighed as M_0. The portion of the homogenised sample was added to the dish, and the weight of the dish + sample = M_1. The sample was dried in an oven for over 4 hours at 105°C, desiccated, and measured the dry weight = M_2. Total solid (TS%) and moisture contents (MC%) can be obtained by:

$$TS = \frac{M_1 - M_2}{M_2 - M_0} \quad (3)$$

$$MS = 1 - TS \quad (4)$$

For volatile contents and ash contents, empty crucibles were evaporated at 550°C for 1 hour. The crucibles were allowed to cool to 100°C in an oven, desiccated to room temperature, and weighed as M_0. The dried sample was added into the crucibles and weighed as M_2. The dried sample was ignited in a furnace at 550° for over 2 hours, cooled in an oven, and desiccated; the ignited weight was measured M_3. Volatile solid (VS%) and ash contents (AC%) were determined as:

$$VS = \frac{M_2 - M_3}{M_2 - M_0} \quad (5)$$

$$AC = 100 - VS \quad (6)$$

An empty container was weighed for density, and the weighing balance was tarred. The sample was put into the container to the brim, weighed, and recorded as the weight of the sample. The container was filled with water (as shown in Figures 3f and 3g). The volume of the water was obtained using a measuring cylinder and recorded as the volume of the container. Density was calculated as:

$$Density = \frac{Mass\ of\ the\ sample}{Volume\ of\ the\ countainer} \quad (7)$$

Energy Content Analysis

The calorific value of the substances was determined by an oxygen bomb calorimeter (GDY-1A) shown in Figure 3i, following ASTM E711-87 [20], the crucible was weighed, tarred, then filled with the sample, fixed on the crucible holder, ends of the ignition wire were connected on the two conductive poles. 10 ml of distilled water was added to the oxygen bomb. Oxygen gas was filled to 3.0 MPa and checked for leaks. The instrument observed and saved the inner bucket's temperature automatically. The liquid was collected and heated to boiling for five minutes. Two drops of phenolphthalein indicator were added and titrated by 0.1N NaOH solution.

Calculations were performed using the following formulas:

$$E = \frac{Q_1 M_1 + Q_2 M_2 + V Q_3}{\Delta T} \quad (8)$$

where,

E = heat capacity of the calorimeter (J/K),
Q_1 = calorific value of benzoic acid (J/g),
M_1 = mass of benzoic acid (g),
Q_2 = calorific value of ignition wire (J/g),

Figure 3 Proximate and energy content analysis: (a, d) weight displacement method for TS, VS, and AC, (b, c, h) lignin, cellulose, and hemicellulose determination for fibre content analysis, (f, g) density, and (i) energy content analysis

M_2 = mass of ignition wire (g),
V = volume of NaOH used (mL),
Q_3 = titration correction for heat of nitric acid (5.9 J/mL for 0.1 mol nitric acid) (J/mL),

$$\Delta T = (t_n - t_0) + \Delta\theta \tag{9}$$

where,

ΔT = temperature increases of calorimeter system after correction (°C),
t_n = final temperature of the primary period (°C),
t_0 = initial temperature of the primary period (°C),

$\Delta\theta$ = the modified value of heat exchange between the calorimeter system and the environment (°C), which can be determined using the Regnault-Pfaund method, shown as:

$$\Delta\theta = \frac{V_n - V_0}{\theta_n - \theta_0}\left(\frac{t_n + t_o}{2} + \sum_{i}^{n-1} t_i - n\theta_n\right) + nV_n \tag{10}$$

where,

V_0 and V_n = the temperature change rate in the initial and final periods, respectively (°C/30 s),
θ_0 and θ_n = the average temperature in the initial and final periods, respectively (°C),
n = number of temperature recordings in the main period,
t_i = temperature reading at sequence i during the main period (°C).

The calorific value of the sample (Q, J/g) was calculated as,

$$Q = \frac{E\Delta T - \sum G_d}{G} \tag{11}$$

where,

ΣG_d = total heat produced by the additive (J),
G = mass of the sample (g).

Fibre Analysis

Amylase-treated neutral detergent fibre (aNDF) content was determined; neutral detergent (ND) solution and heat-stable alpha-amylase is used to dissolve the easily digestible proteins, lipids, sugars, starches, and pectins in biomass, leaving an insoluble fibrous residue that is primarily cell wall components of plant materials (cellulose, hemicellulose, and lignin) and indigestible nitrogenous matter in animal products. EDTA and $Na_2B_4O_7.10H_2O$, distilled water, sodium lauryl sulfate 2-ethothy ethanol (*Ethylene glycol monoethyl ether*), and Na_2HPO_4 were used to make NDF solution following BS EN (ISO 16472) [21]. The solution was neutralised using sulfuric acid and NaOH solutions. An empty, dry muslin bag was weighed. 1 g of the prepared sample was weighed, put inside the muslin bag, and set to reflux. A 100 ml NDF solution was put into the refluxation setup and heated to a boil. The sample was removed from the

reflux and washed twice with hot water and acetone. The sample was oven-dried at 105°C for an hour and weighed.

The percentage of NDF (%NDF) was calculated as:

$$\%NDF = \left(\frac{wt\ of\ the\ bag + sampe - wt\ after\ drying}{wt\ of\ the\ sample}\right) \times 100 \quad (12)$$

Acid detergent fibre (ADF) and acid detergent lignin (ADL) contents were determined by BS EN (ISO 13906) [22] of all insoluble carbohydrates, and protein complexes not removable by neutral detergent were removed, leaving only the lignin, cellulose, and hemicellulose fibres known as ADF. Both cellulose and hemicellulose fibres were removed later using a stronger sulfuric acid, leaving only lignin fibre as a residue called ADL.

Lignin, cellulose, and hemicellulose contents were estimated as:

$$\text{Lignin} = 2.4 \times \text{ADL} \quad (13)$$

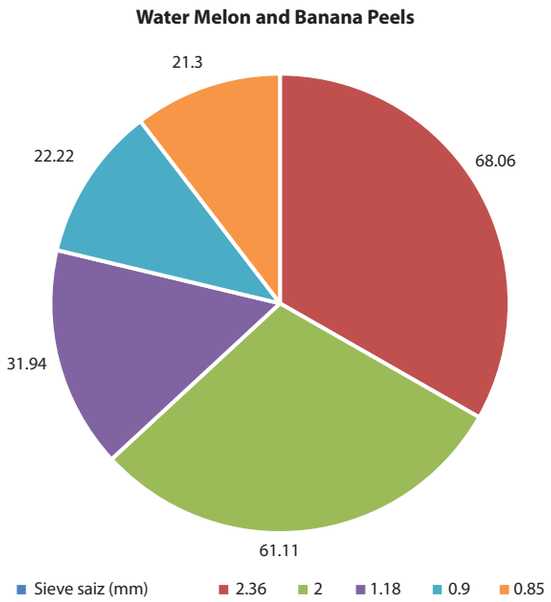
$$\text{Cellulose} = \text{ADF} - \text{ADL} \quad (14)$$

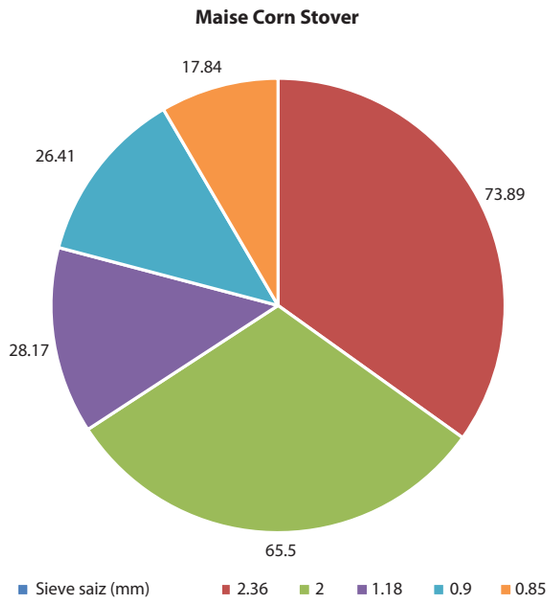
$$\text{Hemicellulose} = \text{NDF} - \text{ADF} \quad (15)$$

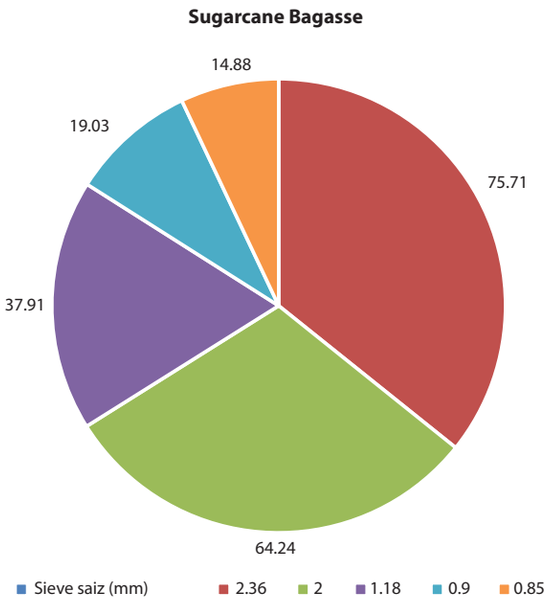
RESULTS AND DISCUSSION

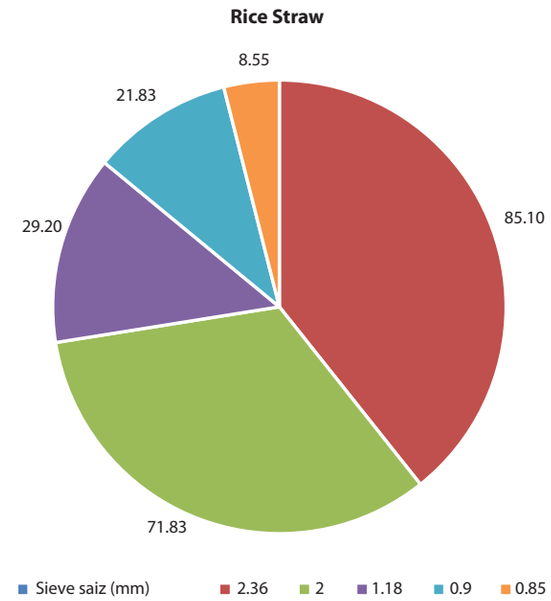
Particle Size Distribution

Figure 4 shows the particle size distribution results obtained from sieve analysis using sieve sizes 2.36 mm, 2.00 mm, 1.18 mm, 0.9 mm, and 0.85 mm, in descending order. The legend at the bottom right corner of Figure 4 indicates the legends. The results indicated that watermelon and banana peels were reduced to 60.87% passing through the 1.18 mm sieve, sugarcane bagasse to 75.71%, maise

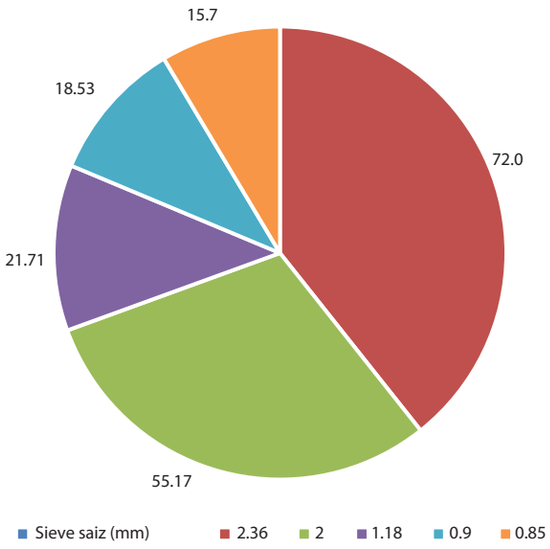




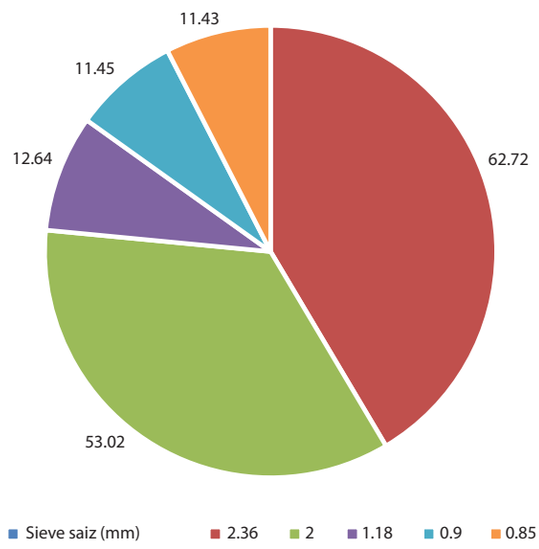




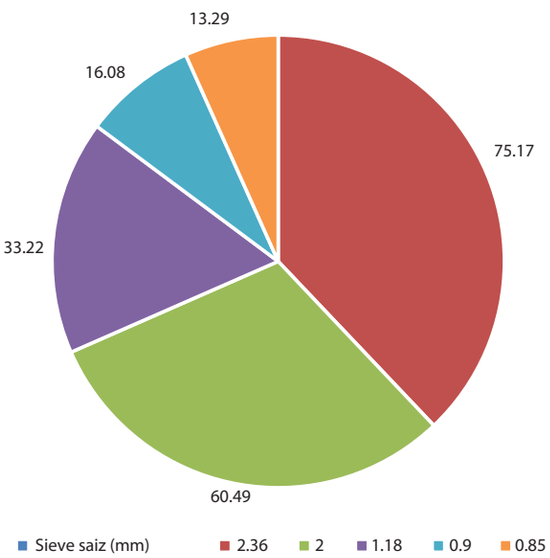
Orange Peels



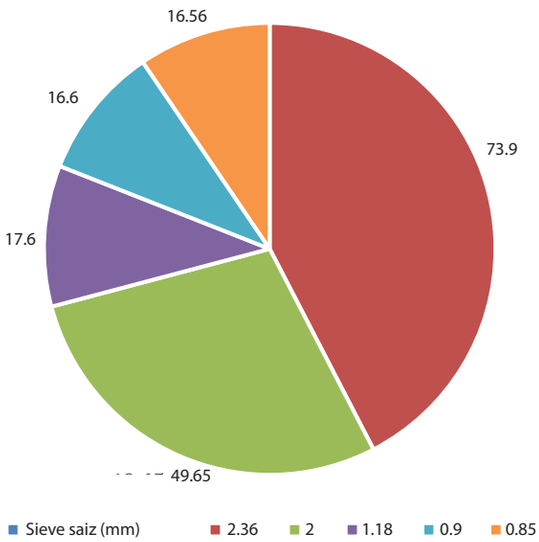
Sorghum Corn Stover



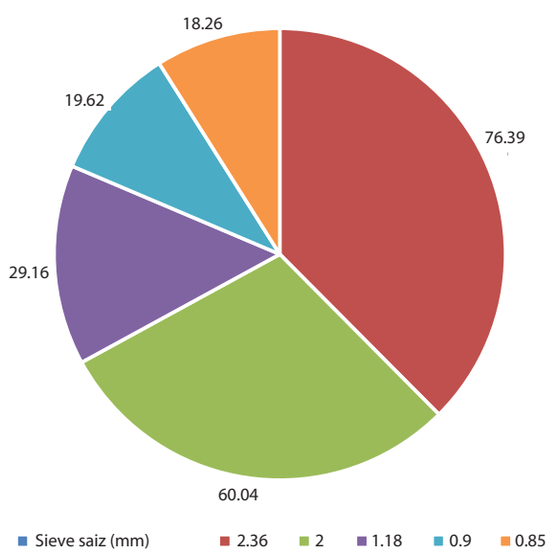
Rotten Sugarcane Bagasse



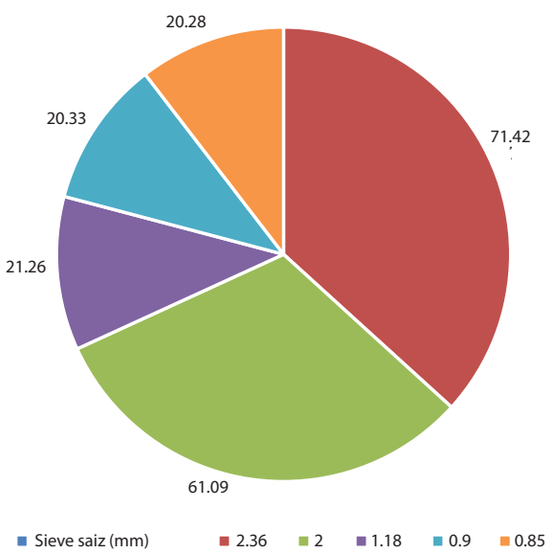
Municipal Waste



Vegetables



Milet Corn Stover



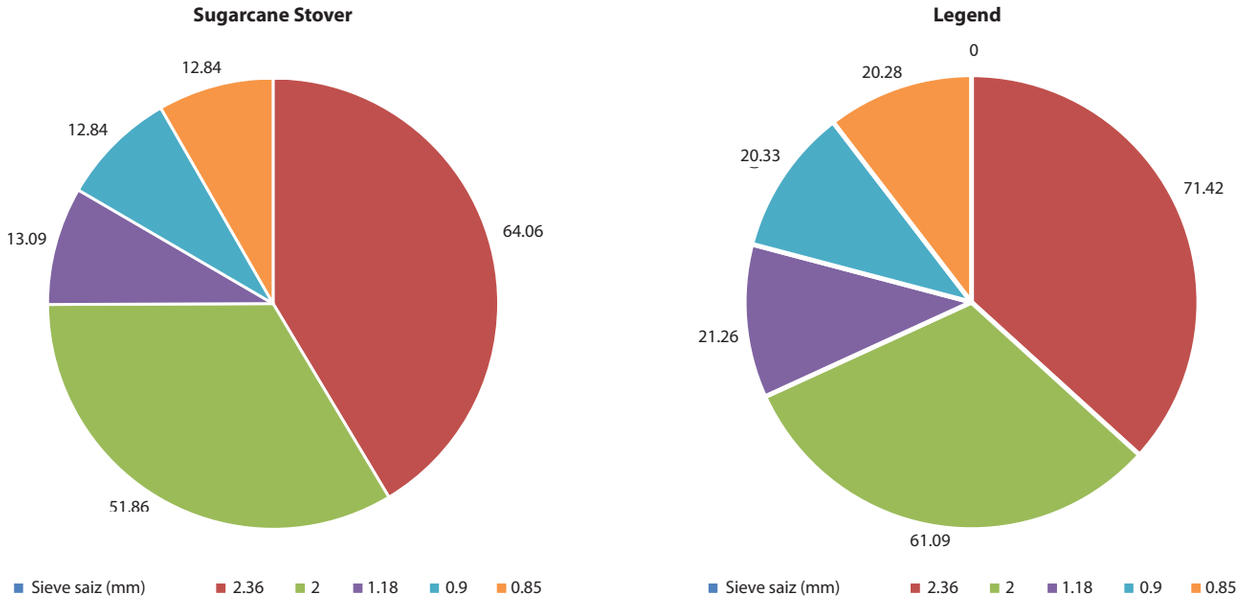


Figure 4 Particle size distribution results of the individual samples with percentage passing the sieves in pie chart

corn stover to 73.89%, rice straw to 85.10%, and orange peels to 72.01%, among others. These findings confirm that the samples are within the workable particle size range.

Colour and Odour Assessment

Table 1 presents results of the organoleptic (colour and odour) analysis. The individual materials exhibit different characteristics in colour and odour; mixtures like watermelon, banana peels, and municipal wastes exhibit complex colour and odour. The observed colour and odour characteristics indicate the presence of lignocellulosic components, ammonia, hydrogen sulfide, and other related compounds. The results in the table conform with [23]-[25]; this shows the potential of the samples to produce bioenergy with appropriate pre-treatments.

Table 1 Results for colour and odour assessment of the individual materials

Samples	Colours	Odours	Discussions
Wet cow rumen content	Light brown	Musty odour with a slightly acidic undertone	Indicates combination of VFAs, NH_3, H_2S and aromatic compounds, microbial byproducts.
Dried cow rumen content	Dark brown	A pungent smell, slightly ammoniacal	VFAs, NH_3, H_2S, dried microbial byproducts.
Watermelon and banana peels	Yellowish brown colour with pecks of green	Complex layered odour with initial notes of fruity smell, later replaced by savoury notes of herbs	Volatile organic carbons VOOC, H_2S, fatty acids and sugars.
Orange	Yellowish brown	Sweet smell with hints of orange	Limonene, aldehydes, and sugars.
Vegetables	Dark brown colour with flakes of tan	The earthy smell, with notes of spicy aroma	Protein, sulphur compounds, sugars and carbohydrates.
Sugarcane bagasse	Light brown	Sweet odour with a slightly grassy smell	Sugars and fibrous lignocellulosic components.
Rotten sugarcane bagasse	Dark brown	A strong and pungent smell	H_2S and organic acids.
Sugarcane stover	Pale green	Subtle earth aroma	Lignocellulosic components and Geosmin.
Maise corn stover	Golden yellow colour	Sweet, earthly, and grassy aroma	Lignocellulosic components and Geosmin.
Sorghum corn stover	Medium brown colour	Earthy and grassy aroma	Lignocellulosic components.
Millet corn stover	Dark brown colour	Subtle sweet smell with a grassy aroma	Alcohols and esters Lignocellulosic components.
Rice straw	Light brown	Hay-like odour	Lignocellulosic components.
Municipal waste	Dark brown	Strong and unpleasant smell with an undertone of ammonia	NH_3, H_2S, and organic acids.

Proximate and Ultimate Analysis

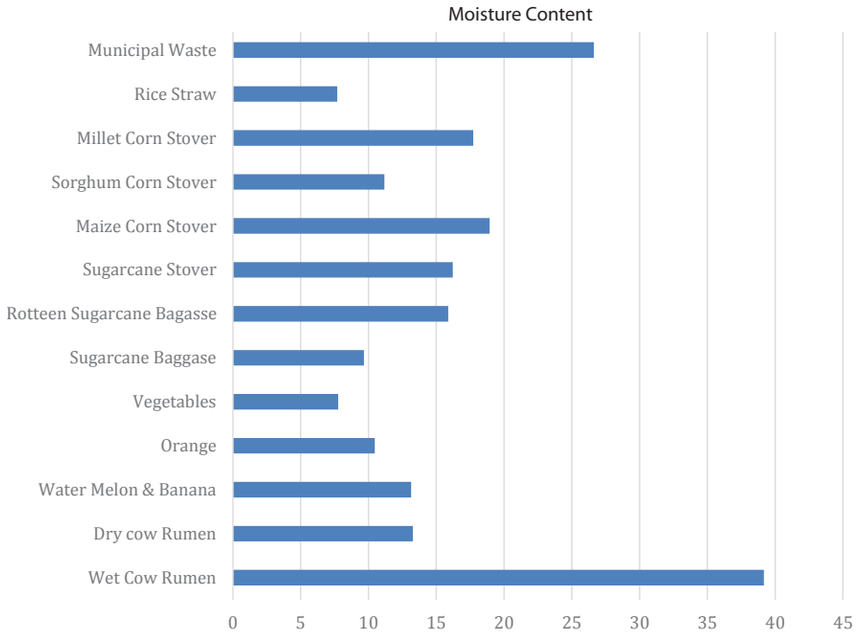
Table 2 and Figure 5 show the results of the proximate analysis, which includes moisture contents, total solids and volatile solids ash content and density for the samples.

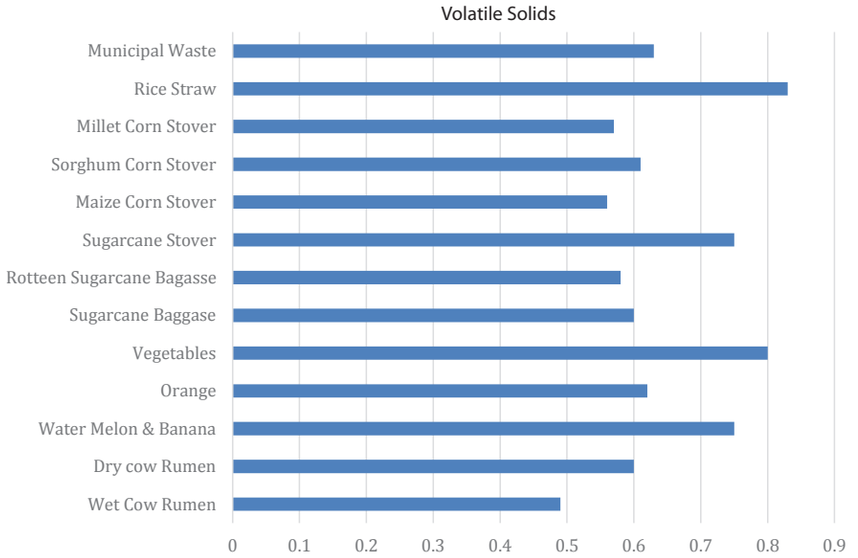
The bar charts in Figure 5 compare the weighted percentage of different biomass samples and the density (g/mL). The results show that wet cow rumen has the highest moisture content, density, total solids, and ash content; municipal waste has the highest volatile solids. For clarity, Table 2 indicates the numerical-value results of the analyses of the samples appropriately.

The proximate analysis results for sugarcane bagasse are consistent with those reported in [26]. However, the results for vegetable and municipal waste show some disparity with those in [27], where the total solids (TS) and volatile solids (VS) for vegetable waste were

Table 2 Numerical value results for the proximate analysis of the samples

	Moisture content %	Total Solids %	Volatile Solids	Ash Content	Density (g/ml)
Wet cow rumen	39.17	92.30	0.49	0.51	1.03
Dried cow rumen	13.28	86.72	0.60	0.40	0.28
Watermelon and banana	13.15	86.85	0.75	0.25	0.16
Orange	10.47	89.53	0.62	0.38	0.36
Vegetables	7.76	92.24	0.80	0.21	0.40
Sugarcane bagasse	9.67	90.33	0.60	0.40	0.43
Rotten sugarcane bagasse	15.89	84.11	0.58	0.42	0.37
Sugarcane stover	16.22	83.78	0.75	0.44	0.17
Maize corn stover	18.95	81.05	0.56	0.44	0.17
Sorghum corn stover	11.18	88.82	0.61	0.39	0.17
Millet corn stover	17.72	82.28	0.57	0.43	0.17
Rice straw	7.70	92.30	0.83	0.17	0.15
Municipal waste	26.63	73.37	0.63	0.37	0.43





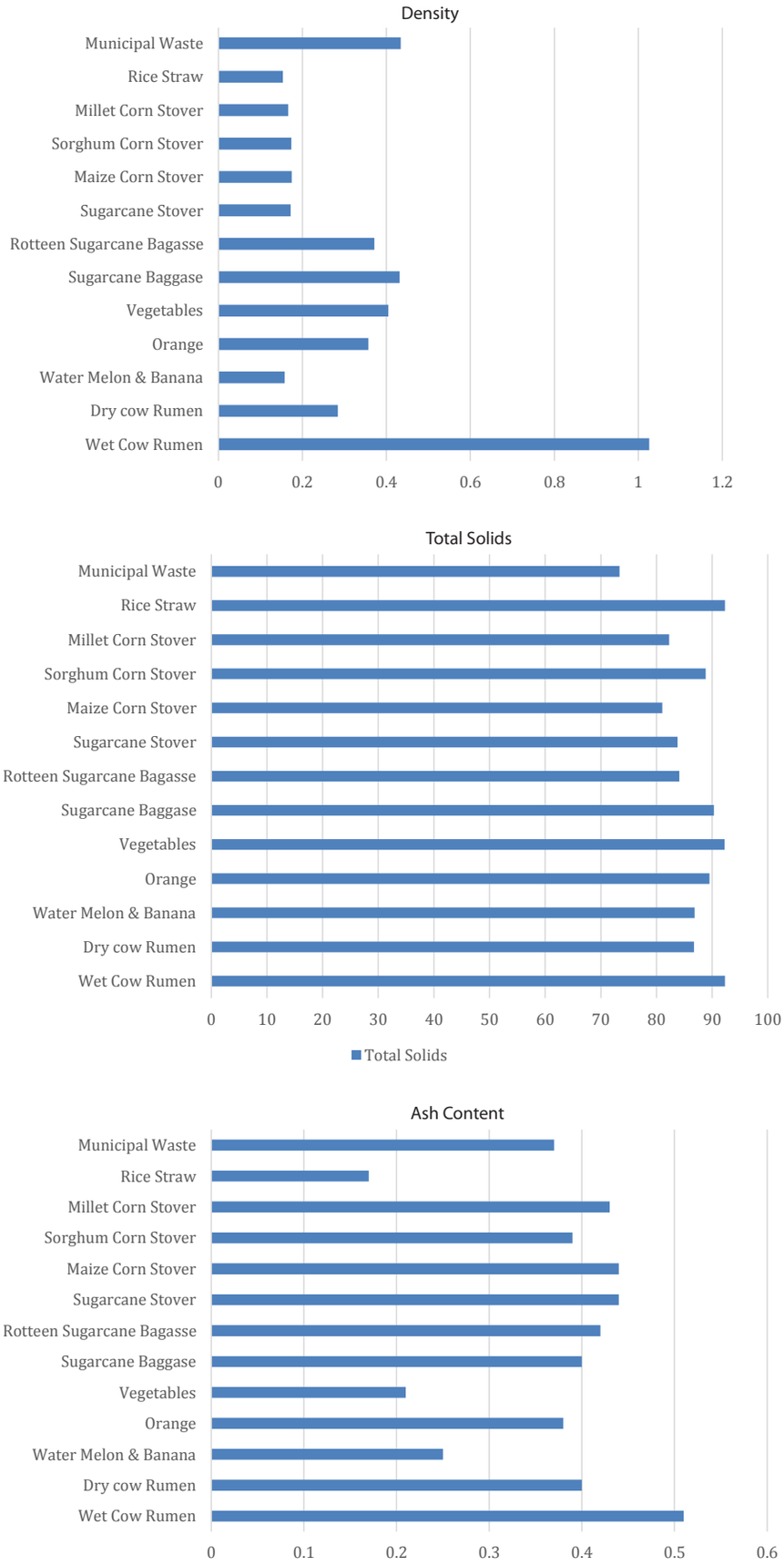


Figure 5 Proximate analysis results in bar chart comparison of the samples

95.9 ± 0.1 and 89.2 ± 0.0, respectively, and for municipal waste, 98.0 ± 0.4 and 94.6 ± 0.0. This discrepancy may be attributed to differences in the composition of the wastes. Similarly, the TS and VS values for cow rumen content, as reported in [28], are 36 and 73.2, respectively, which also differ from the present findings.

Energy Content

Figure 6 presents the materials' calorific values in kJ/kg. The clustered bar charts indicate the energy content of the samples, with vegetable at the highest level (17.64 MJ/kg), maise corn stove at the lowest level (8.24 MJ/kg), and sorghum corn stover at a tie at the lowest level (8.24 MJ/kg).

The heating value of sugarcane bagasse is between 16.91 and 18.73 MJ/kg [26], which is different from the result shown in Figure 6.

Fibre Content Analysis

Table 3 shows the results for the materials' NDF, ADF, and ADL; lignin, cellulose, and hemicellulose were evaluated and presented. From the fibre content analysis, melon and banana peels have the highest lignin content, and municipal waste has the lowest; vegetable wastes have the highest cellulose content, with dry cow rumen having the lowest; maise corn stover has the highest hemicellulose content and melon and banana peels have the weakest.

Results for lignin, cellulose, and hemicellulose from the literature include [29], which reported that rice straw ranges between 12-13, 35-44 and 27-34, corn stover 14-17, 25-31, and 40; sugarcane bagasse 25-30, 20-24, and 40-45. Sugarcane bagasse has 4.7-17.7, 39.9-41.4, and 24-30.9 [26]. Zheng et al. [30] reported that rice straws have 19.2, 34.4, and 29.3. maise stover 10.3, 37.5, and 30. The similarity and disparities of the results may be due to differences in the contents of the samples and geographical location.

Table 3 Results of the fibre content analysis

Samples	NDF %	ADF %	ADL %	Lignin	Cellulose	Hemicellulose
Rice straw	60.80	26.60	6.80	16.32	19.80	34.20
Vegetable waste	52.99	36.73	4.10	9.84	32.63	16.27
Orange waste	50.00	20.90	5.90	14.16	15.00	29.10
Sugarcane bagasse	57.90	29.30	6.90	16.56	22.40	28.60
Rotten SCN BGS	60.92	26.53	5.00	12.00	21.53	34.38
Municipal waste	56.90	30.56	3.90	9.36	26.66	26.34
Maise corn stover	65.80	27.01	6.00	14.4	21.01	38.79
Sorghum corn stover	54.70	32.90	4.90	11.77	28.00	21.80
Millet corn stover	53.90	32.10	5.81	13.95	26.29	21.80
Melon and banana peels	38.98	36.90	8.09	19.42	28.81	2.08
Dry cow rumen	27.40	18.16	6.09	14.63	12.07	9.24

CONCLUSION

Lignocellulosic and carbonaceous biomass, readily available in Northern Nigeria, can be converted from waste into a valuable resource for energy production. The organoleptic parameters (colour and odour) of the samples indicate the presence of diverse components that may influence bioenergy potential, with combinations such as watermelon and banana peels, municipal waste, and vegetable waste exhibiting distinct characteristics. The samples were mechanically processed into smaller pieces to facilitate analysis, and their particle size distribution was determined. Proximate analysis, consistent with findings in existing literature, confirmed the suitability of these materials for bioenergy production. Additionally, fibre content analysis provided valuable insights into the lignocellulosic properties of the various materials, highlighting differences from other reported samples. The results demonstrate the feasibility of sustainable energy recovery from lignocellulosic and carbonaceous biomass, contributing to environmental improvement through reduced carbon emissions

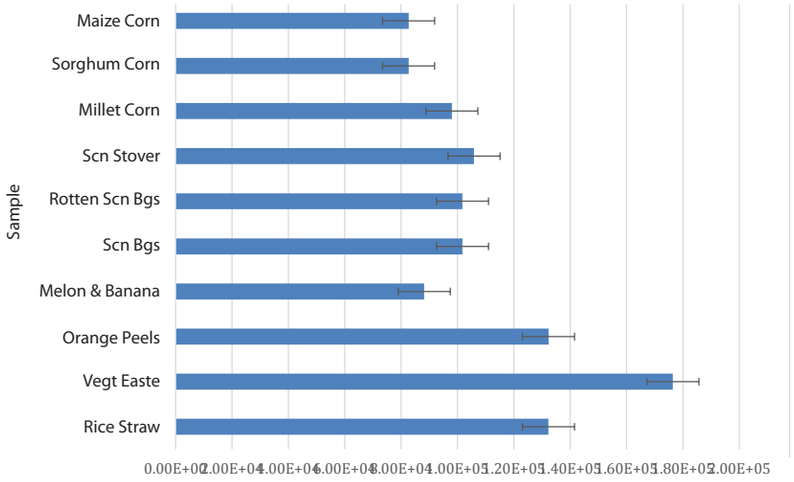


Figure 6 Calorific value of the energy content of the biomass

and better municipal waste management. This comprehensive characterisation and energy potential assessment offer critical data for the modelling, designing, and optimising of bioenergy systems utilising diverse lignocellulosic biomass sources in Nigeria.

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