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Development and Packaging of Eco-friendly Biosolid Briquettes Synthesised with Bagasse for Green Energy Generation and Utilisation

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Abstract

The development of eco-friendly biosolid produced from sugar-cane bagasse for efficient energy utilisation was undertaken. The study investigates the production of carbonised briquettes using selected biomass wastes: coconut husk (CH), corn cob (CC), and sugarcane bagasse (SB) with African locust bean pod powder as a binder. The biomass wastes were carbonised through pyrolysis at 400 °C for 6 hrs to produce biochar. A compressive force of 20kN was applied to the biochar in a cylindrical mould to provide adequate compaction for a desired briquette. Physical, thermal, and combustion characteristics of the biochar were examined. Experimental samples were prepared based on the recommended Standard Methods. Unblended biochar (CH, CC, SB) is classified as 100; whereas, for the blended, 50% mix ratio of CH/CC, CH/SB, and CC/SB. For the three blends CH/CC/SB, a ratio of 33.33% each was employed. Tests were conducted to measure density, moisture content, ash content, hydrophobicity, combustion rate, ignition time, and calorific value. Results showed that CH briquettes had the highest density (1.35 g/cm³), while SB had the least (0.67 g/cm³). Corn cob demonstrated the lowest ash content (9.90%) compared to SB (14.87%) and CH (13.13%), indicating its suitability for clean combustion with less residue. Among blended briquettes, the CH/CC mixture achieved a moderate density of 0.73 g/cm³, and CH/SB achieved 0.97 g/cm³. Moisture content was lowest for CH/CC/SB (6.33%). The hydrophobicity test revealed that CC briquettes exhibited the highest hydrophobicity (26.08%), while CH had the lowest (18.26%). Combustion tests indicated that the CH/CC/SB blend had balanced performance in terms of ignition and combustion rates, making it a viable biosolid for fuel. Corn cob proved to be the best for clean, efficient combustion, while blended briquettes offered a good balance of strength, moisture content, and ash content. These findings highlight the potential of utilizing agricultural waste for green energy, offering a viable alternative to traditional fossil fuels.

Keywords: *Biomass waste, biosolid fuel, briquettes, calorific value, green-energy generation, locust bean pod.*

1.0 Introduction

Generally, managing the increasing volume of biomass waste worldwide has become a major challenge not only in developing countries but also in developed climes. In 2022, the European Union generated over 59 million tonnes of food waste, which amounts to an average of 132 kg of food waste per inhabitant [1]. Of this data average, the household food waste accounts for 54% (71 kg per inhabitant), manufacture of food products 19% (25 kg per inhabitant), restaurants and food services 11% (15 kg per inhabitant), retail and other distribution of food 8% (11 kg per inhabitant and primary production mainly farm 8% (10 kg per inhabitant). In a similar report, the United Nations in 2021 revealed that 37.9 million tonnes of food are wasted annually in Nigeria, amounting to 189 kilograms per person per year, ranking highest in Africa [2]. In another study, it was reported that over 50% of harvested food crops were lost due to poor storage, handling, and transportation [3]. The Nigerian Stored Products Research Institute (NSPRI) provides a range between 50-70% as the total annual post-harvest losses for perishables (fruits and vegetables) in Nigeria [4].

Biomass wastes, including leftover foods, spoiled fruits and other perishables, are amongst the most challenging issues affecting modern societies globally, and are creating significant environmental and socio-economic impacts. Biomass waste represents a fraction of municipal solid waste (MSW), which is largely underutilised. The United Nations (UN) requests that the United Nations Environmental Protection (UNEP) develop a Food Waste Index (FWI) which is based on the Sustainable Development Goal (SDG) Target 12.3. The target states its plan to halve per capita global food waste by 2030 [5]. The indiscriminate dumping of food waste

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in open fields is currently creating health and safety concerns. These ill-actions often produce foul smells, deteriorate the environmental quality, and also contribute to global warming through greenhouse gas emissions.

Derivatives of biomass waste comprised primary (unprocessed food) and secondary (processed food) sources. Crop residues, perishables, maize, cane bagasse, groundnut melon, shea nut, kernel, and coconut shell all form the primary source; while secondary sources are obtained from processed products [6]. Nigeria has substantial biomass waste potential, estimated to reach up to 144 million tons per annum [7]. It is observed that the rural and semi-urban dwellers are using biomass waste to meet their energy needs. Biomass waste comprising crop residues, wood, charcoal, animal dung, and saw-dust briquettes accounts for about 80% of the total primary energy consumed in Nigeria [8]. Table 1 provides data on the sources and amount of biomass waste produced from different crop yields in Nigeria for green energy generation.

Table 1: Estimated agricultural crop residues for selected crops in Nigeria

Biomass Waste	Production (x10^3) ton	Residue Type	Total residue (Million tons)
Rice	3368.24	Straw	8.64
		Husk	1.19
Maize	7676.85	Stalk	19.59
		Cob	2.1
Groundnut	3799.25	Shell	1.54
Sugarcane	2481.51	Bagasse	127.6
Cotton	602.44	Pod	9.68
Millet	5170.45	Straw	8.93
Cowpea	3368.24	Pod	9.77

Source: Getu *et al.* [12]

A study in 2018, reported that over 70% of the global energy demand relied on coal, oil, and natural gas for economic and industrial growth, resulting in energy-related carbon emissions by 1.7% [9]. According to estimates, the global recoverable oil reserves are diminishing at a rate of 4 billion tons per annum [11]. Hence, a transition to alternative green energy sources is highly desirable [10] and biomass offers such alternative.

The utilisation of biomass waste (sugarcane bagasse) as an energy source is attracting research interest [9]. Sugarcane consists of 25 - 30% bagasse and sugar crystals 10% [10], suggesting a significant amount of waste. Cane bagasse, with 50% or less of reduced moisture content, has the potential for a high calorific yield of about 15.98 – 19.17 MJ/kg [10]. But, to improve the energy properties of biomass, it needs to be converted to an energy reach carbon material close to the natural coal. The available thermochemical conversion processes include carbonization, torrefaction, pyrolysis, gasification and hydrothermal carbonization [13 – 31]. But, for convenience, this study considered slow pyrolysis for the conversion of the feedstock to biochar. To this end, this study aims to explore the potentials of developing sustainable; eco-friendly biosolid briquettes produced form cane bagasse for green energy generation and utilisation.

2.0 Materials and Methods

2.1 Description of Locations for Biomass Materials Collection

The following biomass waste (feedstock) such as Coconut husk (coir), sugarcane bagasse, and corn cob and other food waste (Figure 1) were all sourced from a processing unit at Kure Ultra-Modern Market, Minna, Niger State, which is located on the following coordinates: Lat (9 º 36′ 55.76″ N); Long (6º 31′ 52.6″ E). The African locust bean pods (Figure 1d) used as binder were obtained from mature trees in a rural area of Kabba, Kogi State, located on coordinates Lat (7 ° 50′ 00″ N); Long (6 04′ 00″ E) while some of the equipment used are shown in Table 2.

Figure 1: (a) Coconut Husk (b) Corn Cob (c) Sugarcane Bagasse (d) Locust Bean Pod (e) Ground Locust Bean Powder (f)Locust Bean Slurry (g) Fruits and Vegetable Waste

Table 2: Equipment and instruments used in carrying out this study

Equipment	**Instruments/Auxiliaries**
Small Portable Crusher	Digital Weighing Balance (Model: AR3130 OHAUS Corporation China)
Hydraulic Press	Thermometer
Grinder	Digital Oven ((Model: PBS118SF Genlab Widnes England)
Sieves	Vernier Caliper
Fabricated Bioreactor/ briquetting furnace	Stopwatch Pale/Bowl
Bomb Calorimeter	
Small laboratory Blender	
Bunsen Burner	

2.2 Sample Preparation and Pre-treatment

Upon collection of the biomass waste from Abdulkadir Kure Ultra-Modern Market, Minna, the waste samples were crushed and ground using a hammer mill and a kitchen blender, and sieved using a standard sieve mesh to obtain 0.60 mm particle size. The biomass wastes were then washed to remove dirt and other foreign materials before rinsing thoroughly with de-ionised water. The resized biomass wastes were oven-dried at 105 ^{o}C for 24 h. The process of carbonisation was carried out in a barrel kiln furnace at a temperature of 400 ^{o}C for 6 hrs to produce biochar, which was later exhumed from the carbonisation chamber and allowed to cool at a room temperature of 25 °C for 24 hrs The carbonised biochar was stored in a container with a lid, set for conversion into briquettes. A measure of 500 g dried ground locust bean pod (binding agent) was mixed with 500 mL of water to form a slurry. To prepare the slurry, a procedure outlined by [31] was adopted. The slurry is shown in Figure 1 (e and f).

The biochar, bagasse, and binder were mixed and transferred into a cylindrical mould of the following dimensions: Diameter (Ø) 20 mm, and height (H) 40 mm. A ratio of 60% biochar, 30% pod powder as binder, and 10% stratified bagasse was mixed with the slurry poured into a pre-mould cylindrical cast iron to its capacity before lowering the lid. A load of 20 kN was applied to provide adequate compressive force to produce the desired solid briquette as illustrated in Figure 2.

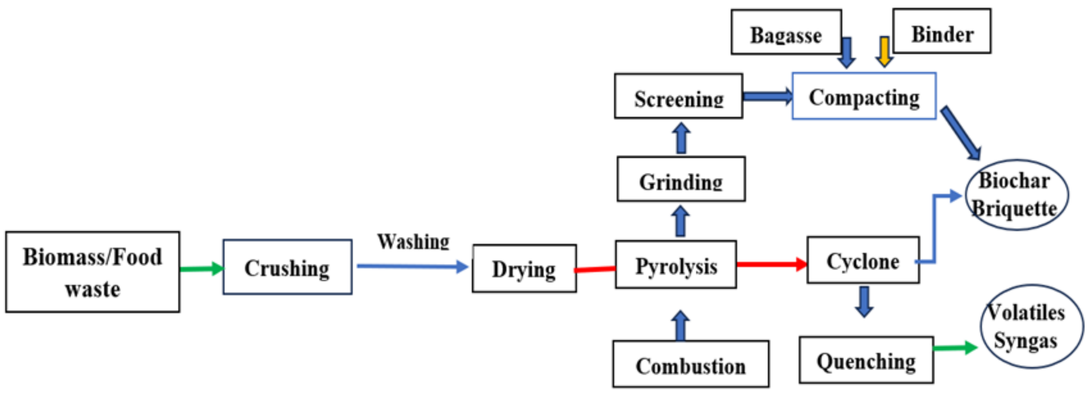

Figure 2: Block Diagram step-wise pyrolytic process for converting biomass waste to biochar

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2.3 Proximate Analysis of Produced Briquettes

Proximate analyses to determine the constituents of the produced briquette were carried out at the Laboratories of Genetic Engineering and Biotechnology, Step-B Funded Centre of Excellence and Nanotechnology, Bosso Campus, Federal University of Technology, Minna.

2.3.1 Determination of Moisture Content

The moisture content (%) of the biomass waste was determined on a dry weight basis using the recommended standard, as described in the American Society for Testing Materials (ASTM D 4442-07) [33]. The moisture content was calculated from a known weight (W_1) of briquette before oven drying and weight (W_2) after drying at a preset temperature of 105 °C for 24 hrs. The difference in weight, calculated as a percentage of the moisture content was obtained using Equation 1.

$$MC = \frac{W_1 - W_2}{W_1} * 100 \quad (1)$$

Where;
MC = Moisture Content (%)
W_1 = Initial weight of sample before drying (g)
W_2 = Final weight of sample after drying (g)

2.4 Ash Content

The Ash Content (AC) was determined using the recommended method as described in CEN/TS14775 [34]. This involved weighing and heating 2 g of pulverised stratified biochar in a desiccator inserted into a furnace preset at 550 °C for 4 hrs. At the expiration of the time, the biochar sample was brought out of the furnace and allowed to cool before re-weighing to determine the ash content. The following equation was used to calculate the ash content:

$$AC\ (\%) = \frac{W_f}{W_i} * 100 \quad (2)$$

Where;
AC = Ash Content (%)
W_i = Initial weight of dry sample (g)
W_f = Final weight of ash obtained after cooling sample (g)

$$VMC\ (\%) = \frac{W_i - W_f}{W_i} * 100 \quad (3)$$

Where;
VMC = Volatile Matter Content (%)
W_i = Initial weight of dry sample (g)
W_f = Final weight of ash obtained after cooling sample (g)

2.5 Fixed Carbon

The Fixed Carbon Content (FCC) of the biochar was determined as a percent by subtracting the total of Moisture Content (MC), Ash Content (AC), and Volatile Matter Content (VMC) from 100, as presented in Equation 4.

$$FCC = [100 - (AC + MC + VMC)]\% \quad (4)$$

2.6 Determination of Briquette Volume

The briquette volume was calculated (Equation 6) based on dimensions such as cylindrical briquette height and radius. Using a vernier caliper, the radius and height of the cylindrical briquettes were measured to determine the volume of the resulting briquette. Equation 6 was used for the calculation.

$$V = \pi r^2 h \quad (6)$$

Where;
V = Volume of the cylindrical briquette (cm^3)
r = Radius of the briquette (cm)
h = Height of the briquette (cm)

Equation 7 was used to calculate the radius of the briquette

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$$r = \frac{d}{2} \quad (7)$$

Where;
d = diameter of briquette (cm)

2.7 Determination of Briquette Density

To calculate the density, the mass of the briquettes was measured using a digital weighing balance as outline in ISO Standard 3131 [35]. The density was then calculated using the relationship in Equation 5.

$$\rho = \frac{m}{v} \quad (5)$$

Where;
ϱ = density of the material (g/cm^3)
m = mass of the material (g)
v = volume of the material (cm^3)

2.8 Determination of Shattering Index

ASTM D5276/ISO 616:2021, Standard Test Method was used to determine the Shattering Index or percent mass loss (%) of the produced briquettes [36]. The drop test was performed from a specific height of 2 m to observe breakages due to impact force. This is a plausible way to measure the mechanical durability of the briquette. **The Percentage Mass Loss (PML) was calculated using Equation 8, then, the Shatter Index (S.I) was calculated using Equation 9.**

$$PML\ (\%) = \frac{M1-M2}{M1}\times 100 \quad (8)$$

Where; **.**
PML = **Percentage Mass Loss (%)**
M_1 = Initial mass of briquette before drop test (g),
M_2 = Final mass of briquette after shattering (g)

$$S.I = (100 - \%\ Mass\ Loss) \quad (9)$$

Where;
S.I = Shatter Index (%)

2.9 Hydrophobicity Test

To demonstrate the period taken for briquettes to disintegrate when submerged in water, a hydrophobicity test was carried out. This test was conducted based on the Standard Method, as described in ASTM: FF 22-13 [37]. Hydrophobicity (%) of the briquette was calculated using Equation 10,

$$WAC\ (\%) = \frac{W_f - W_I}{W_f} * 100 \quad (10)$$

Where;
WAC = Water Absorption Capacity *(%)*
W_i = Initial mass of briquette (g)
W_f = Mass of wet briquette (g)

$$Hydrophobicity\ (\%) = (100 - WAC) \quad (11)$$

2.10 Determination of Combustion Rate

The amount of time taken for a 1.5g briquette to ignite and allowed to completely burn into ash is termed as the burning time. The combustion rate (CR) was then calculated using Equation (12), which follows the path as described by ASTM E1354-24 [38].

$$CR = \frac{Md}{Td} \quad (12)$$

Where;
CR = Combustion Rate (g/min)
M_d = Mass of burnt briquette (g),
T_d = Total time taken (mins)

2.11 Determination of ignition time

The briquette aggregates were prepared of uniform size, shape, and moisture content (dried consistently). An ignition source (matchstick) was positioned at a specific point (4 cm) beneath the briquette placed on the Bunsen burner before being lit. A stopwatch was used to record the time taken from the inception of ignition until a sustained blue flame was observed, to provide the burning phase. This was performed, using Equation 13, following the procedure outlined in [12]

$$I_T = \frac{\textbf{Time taken to Ignite from Source}}{\textit{Time taken to sustain the flame}} \quad (13)$$

Where;

I_T = Ignition Time (sec)

2.12Determination of Biochar Yield

The biochar yield was determined using Equation (14).

$$Biochar\ yield\ (\%) = \frac{weight\ of\ carbonised\ biomass\ materials(g)}{Initiial\ weight\ of\ biomass\ waste\ (g)} \times 100 \quad (14)$$

2.13 Calorific Value

The calorific value (CV) of the briquette was determined using a Bomb Calorimeter available in the Laboratory of Genetic Engineering and Biotechnology (Step-B Funded Centre of Excellence and Nanotechnology, Bosso Campus, Federal University of Technology, Minna. A sample of the briquette was collected and subjected to an Adiabatic Oxygen Bomb Calorimeter (Parr 6200 calorimeter). The procedure for this test was based on the standard method described in ASTM D-5865-95 [39].

2.14 Data Collection and Analysis

Briquetting data collected in the course of conducting this study were analysed using Analysis of Variance (ANOVA) as a statistical Tool to compare means (X) and standard deviation (SD) of the sample data. Trial tests were carried out in triplicate (n=3).

3.0 Results and Discussion

3.1 Yield of Biochar

The yield of biochar after carbonization was determined as 96.2% for sugarcane bagasse; while the least of 91.6% recorded for coconut husk. Table 3 presents summarized yield of all the samples used.

Table 3: Yield of the produced biochar

Biomass Materials	Initial Weight (g)	Final Weight (g)	Biochar Yield (%)
CH	500	42.14	91.6
CC	500	35.42	93.0
SB	500	19.16	96.2
CH-CC	500	22.97	95.4
CH-SB	500	28.13	94.4
CC-SB	500	21.96	95.6
CC-SB-CH	500	22.45	95.5

3.7 The Produced Briquettes

Figure 3 shows compacted pyrolysed biochar briquettes produced with sugarcane bagasse as product of the research study.

Figure 3: Carbonised biochar briquettes

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3.1 Proximate Value of Briquettes Produced

3.1.1 Moisture Content

The proximate analysis carried out on the unblended carbonised briquettes revealed varying moisture content levels (Figure 4) of the produced briquettes. The CH and CC measured 11.5% (≈ 0.345 g) and 11.6% (≈0.348 g) respectively, as moisture content. The SB measured 7.97% (≈ 0.239 g), which is lower than those recorded in CH and CC. This indicates that SB absorbs less moisture compared to CH and CC. Findings from this study are in agreement with [40] that high moisture in briquettes often leads to a drop in both thermal efficiency and burning rate. This suggests that briquettes required for energy generation should have very low moisture content. On the other hand, blended briquettes were observed to have lower moisture content compared to unblended briquettes, which indicates improvement in their combustion performance. CH-CC has a moisture content of 5% (0.15 g), while CH-SB shows 7.67% (0.23 g). The CC-SB blend has a moisture content of 6.93% (0.208 g), and the lowest recorded in CC-SB-CH, with 6.33% (0.19 g). According to the above, all blended briquettes were observed to have lower moisture content compared to the unblended, which tend to produce an enhanced briquette with better combustion efficiency and reducing drying time. Figure 3 shows the moisture content in percentage and grams of briquettes produced from coconut husk (CH), corn cob (CC), and sugarcane bagasse (SB) mixed in different proportions using African locust bean pods as binder.

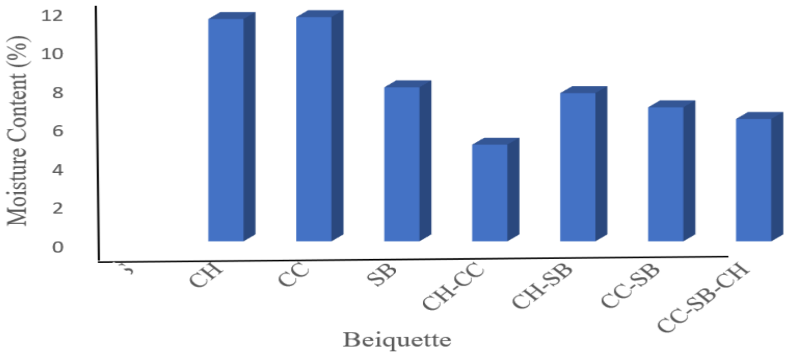

Figure 4: Present Moisture Content of the Briquettes

3.1.2 Proximate Values on Ash Content

Figure 5 presents the ash content generation of each feedstock. The food waste (FW) which forms part of the biomass wastes considered in this study is mainly of vegetables and fruits, which measured the highest ash content of 18.0%, followed by sugarcane bagasse (SB) producing 14.87%, then coconut husk (CH), 13.13% as ash content and the least recorded from corn cob (CC) as 9.90%. It was observed that the briquette contained non-combustible materials. This suggests that the unblended briquettes generate more ash during combustion, which ultimately results in low energy density and burning efficiency. A blend of CH-CC produced 15.10% of ash content, while CH-SB generated 17.23%, and CC-SB measured 14.13%. This implies that, while the briquettes might offer improved binding characteristics, they all produce ash that equates to those obtained in the unblended. A blend of feedstock (CC-SB-CH) produced an ash content of 16.60%, indicating a significant accumulation of non-combustible material. The high ash content certainly would affect the energy output and combustion efficiency of the briquettes. Findings from this study also align with the work reported by [40].

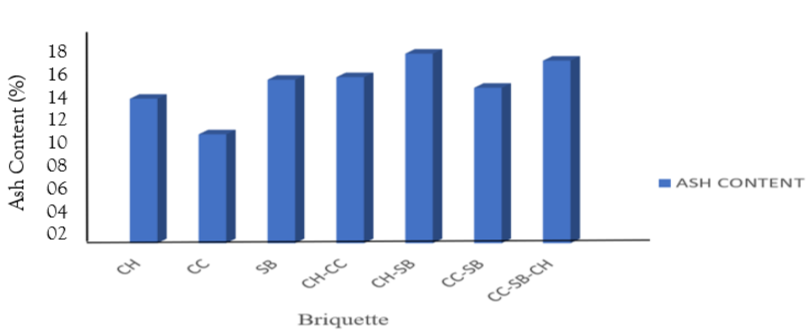

Figure 5: Ash content of the produced briquettes

3.1.3 Hydrophobicity

The hydrophobicity (Figure 6), which measures a material's ability to repel water, is an important test for the durability and storability of briquettes. High hydrophobicity indicates better water resistance, while those with low values suggest the material absorbs more moisture, which could negatively impact combustion efficiency and handling. In this study, as illustrated in Figure 5, the hydrophobicity of CH is 89.0%, which is the lowest among the individual biomasses. This indicates that briquettes made from CH are more likely to absorb water, potentially affecting their combustion efficiency, especially when stored in humid conditions. Moisture absorption can lead to difficulty in ignition and lower calorific value. The CC has the highest hydrophobicity of 92.3%, meaning it has the best water-repelling properties among the individual samples. This makes briquettes made from CC more durable and resistant to moisture, particularly in regions with high humidity. On the other hand, the SB measured hydrophobicity as 91.0%, which is considered moderate. The blend is observed to have a better water-repellent tendency than CH but less than CC. Briquettes made from SB may perform well but could be slightly less resistant to moisture compared to those made from CC. On the other hand, the blend of CH-CC has a hydrophobicity of 91.2%, appearing to range between those of CH and CC, 89.0% and 92.3%, signifying that the combined effect offers an improved water resistance ability. Similarly, the hydrophobicity of the CH-SB blend is evaluated as 91.8% approximately that of CC. This is same for CC-SB blend with hydrophobicity of 90.7%, which is slightly lower than values obtained for both CC and SB. This suggests that all blends have the inherent characteristics for moisture resistance; however, the hydrophobicity test on CC-SB-CH blend reveals 89.8%, which forms the lowest among the blends. Generally, the values obtained for hydrophobicity tests indicate that both blended and unblended briquettes are within acceptable limits of water-repelling ability.

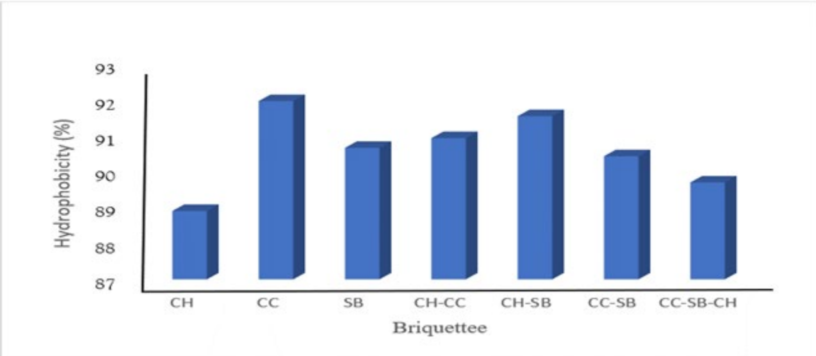

Figure 6: Hydrophobicity test of briquettes from various biomass waste

3.1.4 Percent Volatile Matter Content

The volatile matter content (Figure 7) is an essential factor in determining the combustion quality of briquettes. In this study, Figure 6 shows that CH has the highest volatile matter content at 77.23%, which indicates that the briquette releases a necessitates a significant quantity of volatile gases during burning, which also necessitates rapid ignition into flame. The CC and SB display moderate volatile matter contents of 62.03% and 64.33%, respectively. The least volatile matter content was found among the blends; CH-CC produced 59.07%, resulting in slow burning compared to the unblended. The CH-SB measured volatile matter content of 62.67%, suggesting appreciable combustion characteristics due to synthesis with sugarcane bagasse. Similarly, the CC-SB blend shows a higher volatile matter content of 65.93%, which enhances ignition and burning rate, thereby making it most suitable for fast heating. Whereas, CC-SB-CH: measured 62.07% as volatile content, indicating a promising burning rate and ignition properties; though moderate smoke output was observed, which may be due to incomplete combustion. Based on the above, the researchers were able to establish that a high percentage of volatile matter content implies a faster and more vigorous burning effect, while the lowest percentage suggests slower combustion.

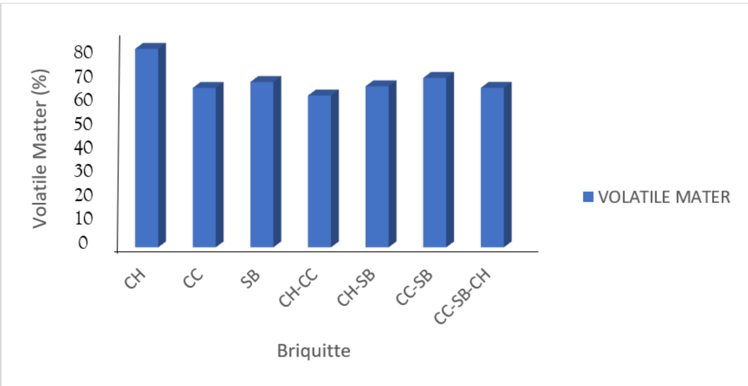

Figure 7: Volatile matter content of each briquette

3.2 Evaluation of Physical Properties of Produced Briquettes

Table 4 shows the physical properties of the produced briquettes. Evaluation of the physical properties (weight, volume, and density) of the carbonised briquettes measures weight of CH as 42.14g, 31.11 cm^3 as volume, and density of 1.35 g/cm^3; indicating in contrast, food waste (FW) has the least density of 0.62 g/cm^3 with a weight of 12.45 g and volume of 20.14 cm^3, making it the lightest and least dense briquette (see Table 4). Whereas, CC has similar volume of 30.75 cm^3; 1.15 g/cm^3 as density, and 35.42g dry weight, which infers minimal difference. However, the blends of CH-CC briquettes have a density of 0.73 g/cm^3, lower than either of the unblended CH and CC. The CH-SB briquette has a density of 0.97 g/cm^3. A blend of the three feedstocks (CC-SB-CH) produced a density of 0.81 g/cm^3, slightly higher than the CC-SB blend (0.81 g/cm^3), but both have moderate densities and weights, offering a good balance between strength and lightness. On the other hand, the volume of the carbonised briquettes shows consistent values across all samples, with only slight variations. Consequently, the blended briquettes also demonstrate close volumes: CH-CC has a volume of 31.45 cm^3, and CH-SB has 28.91 cm^3, maintaining consistency with the individual materials. The CC-SB and CC-SB-CH blends show slight reductions in volume, which measure 27.24 cm^3 and 27.73 $cm^{3,}$ respectively. These slight variations in volume across the samples suggest that the briquette sizes remain relatively stable regardless of the material composition, weight and density. Hence, this suggests that the blended CH, formed the densest briquettes, while SB recorded the least. This situation enables a quick ignition of the briquettes, which eliminates the need for an external blower or booster. In essence, the blended samples show varying densities, which offer flexibility depending on desired briquette properties.

Table 4: Physical properties of briquettes produced

Sample	Weight (g)	Volume (cm^3)	Density (g/cm^3)
CH	42.14	31.11	1.35
CC	35.42	30.75	1.15
SB	19.16	28.40	0.67
FW	12.45	20.14	0.62
CH-CC	22.97	31.45	0.73
CH-SB	28.13	28.91	0.97
CC-SB	21.96	27.24	0.80
CC-SB-CH	22.45	27.73	0.80

3.3 Evaluation of shattering index of briquettes

Figure 8 depicts the shattering force (N) against the unblended and blended briquettes. Coconut husk (CH) and corn cob (CC) have the highest shattering forces of 141.6 N and 144 N, respectively. Indicating their restiveness to breaking due to impact force (N). The shattering force led to producing corresponding shattering indices of 12% (a CH) and 3% (CC), suggesting that the CC briquettes are more durable. The SB recorded much lower shattering force of 14.2 N, indicating non-durability, producing a high shattering index of 16%. In the case of the blends, CH-CC measured shattering force of 22.5 N with a corresponding shattering index of 14%, suggesting that the blend of CH and CC was observed to have slightly reduced the durability compared to the unblended. CH-SB and CC-SB recorded the least shattering forces of 6.3 N and 7.8 N, respectively, with very high shattering indices of 7.0% (CH-SB) and 4.1% (CC-SB). This informed the reason why the blends to be more susceptible to breakage than the unblended CH and CC. However, CC-SB-CH, with a low shattering force of 18.6 N and 5.0% as shattering index, depicts a level of non-durability. In essence, the unblended CH and CC were observed to be most durable, with SB (0.6%) being the least resistant to shattering.

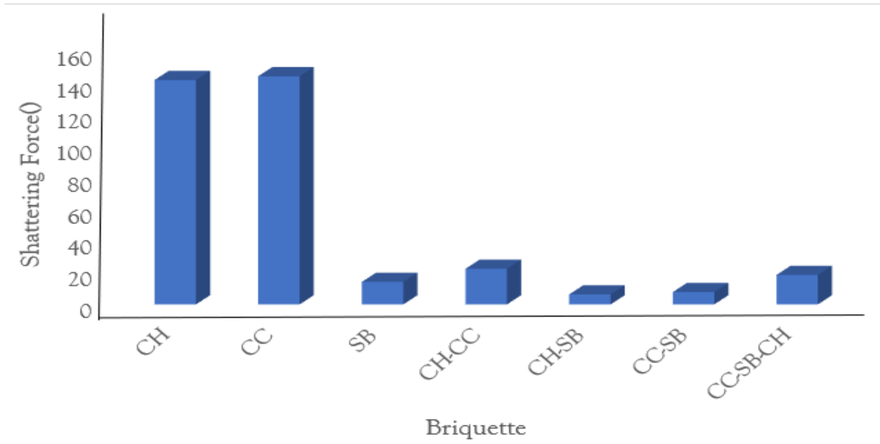

Figure 8: Shattering force of the various biochar briquettes

3.4 Evaluation of Ignition Time of Briquettes

The ignition time data (Figure 9) reveals differences in how quickly the various briquette samples ignite, highlighting the impact of material composition on the combustion process. The CH has a higher and faster ignition time of 17.46 sec. In contrast, the CC exhibits the slowest ignition time at 32.52 sec, indicating that CC briquettes take a longer time to star-up the fire, which may possibly be due to their dense structure and lower volatile matter content. However, the fastest to ignite was the SB with an ignition time of 25.41 sec. This suggests that SB offers a balance between fast ignition and sustained burn. For the blended briquettes, the CH-CC blend ignites has the slower ignition time of 12.43 sec, indicating that blending CH with CC results in faster ignition compared to that observed in unblended CC or CH. The CH-SB blend, with an ignition rate of 23.12 sec, is similar to that recorded in SB. The CC-SB blend exhibits the fastest ignition time at 6.41 sec, indicating that the blend produces a very quick-fire start-up due to the inherent combustion properties of SB and CC. The CC-SB-CH blend also shows a quick ignition time of 16.88 seconds, which is better than unblended CH and CC briquettes.

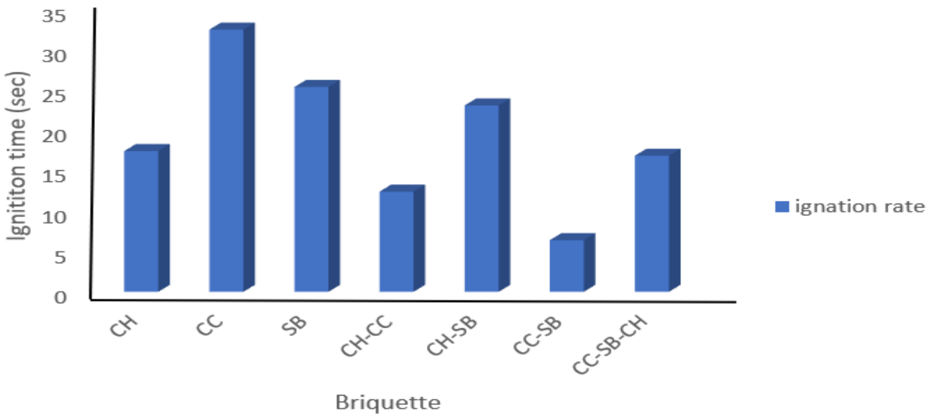

Figure 9: Ignition time for the produced briquettes

3.5 Evaluation of the Combustion Rate of the Briquettes

Figure 10 shows the various combustion rates of the produced briquettes. The combustion rate and combustion time data provide valuable insights into the burn efficiency of the different briquette samples. The CH has a combustion rate of 0.6472 min/g and a combustion time of 185.4 sec, indicating it burns moderately fast. While CC has a slower combustion rate of 0.4717 min/g, with a combustion time of 254.4 seconds, which implies a slow burning rate. This is beneficial for applications. On the other hand, the SB measured a combustion rate of 0.5682 min/g and a combustion time of 211.2 sec. However, the blended briquettes display diverse combustion characteristics. For instance, the CH-CC blend has a higher combustion rate of 0.961 min/g and a shorter combustion time of 124.8 sec, suggesting that blending CH with CC increases the burning rate, which makes the briquette less efficient for long-duration applications. CH-SB has a combustion rate of 0.63 min/g and burns for 190.8 sec. The CC-SB blend exhibits the highest and best with a combustion rate of 1.36 min/g for a combustion time of 88.2 sec, indicating that this combination burns very rapidly, possibly leading to higher heat output but shorter burning time. The CC-SB-CH blend was observed to have a combustion rate of 0.82 min/g and a burning rate of 146.4 sec. In this context, the blends appear to have faster combustion rates compared to the unblended.

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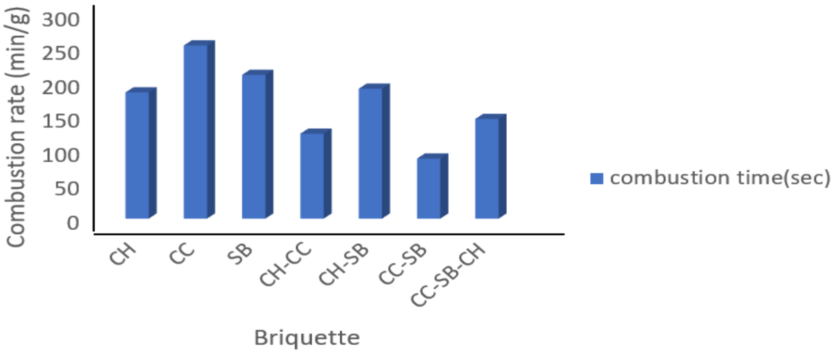

Figure 10: Combustion rate of produced briquettes

3.6 Evaluation of Calorific Value of the Produced Briquettes

The heating/calorific value regulates the energy content of a fuel. It is a property of biomass fuel that can be influenced by moisture content and chemical composition. When 90% of carbonised biochar was mixed with 10% of African locust bean pod slurry as a binder, the briquette produced a caloric value of 4442 Cal/g,. Still, it decreased to 3964 Cal/g when the ratio of slurry increased to 25% mixed with 75% biochar. High calorific value makes combustion more efficient; thereby, reducing the quantity of briquettes used.

4.0 Conclusion

Briquettes were produced from CH, SB, and CC, using African locust bean pods as a binder, as an eco-friendly biosolid for green-energy generation. Analysis of the samples revealed that CH had the highest density (1.35 g/cm³). In comparison, SB had the least (0.67 g/cm³), indicating significant variability which can be attributed to the inherent biomass waste composition and briquette density. The moisture content was lowest for the CH-CC-SB blend at 6.33%, which favours combustion compared to the unblended CH and C with 11.5% and 11.6%, respectively. The CH-CC blend showed the highest combustion rate at 0.961 min/g, while CC recorded the slowest at 0.472 min/g. The ash content of the CC briquette was recorded as the lowest (9.90%), and CH-SB had the highest (17.23%). For the hydrophobicity, CC is considered to be the most resistant to moisture with a hydrophobicity value of 92.3%. In comparison, CH exhibited the least, 89.0%, indicating that CC-based briquettes are ideal for humid storage conditions. The outcome of this study revealed that CC is best for prolonged heat generation and with low ash output and when mixed with SB, it offers a better heating efficiency. Therefore, this research showed the potential of utilising biomass wastes for a sustainable energy production.

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References

[1] Eurostat Food Waste: 132 kg per inhabitant in the EU in 2022. https://ec.europa.eu/eurostat/web/products-eurostat-news/w/ddn-20240927-2, 2024, September 27.

[2] United Nations Environment Programme. Food Waste Report 2021. Nairobi. https://www.unep-food-waste-index-report-2021, 2021.

[3] Food and Agriculture Organization of the United Nations; FRCN HQ, 2025; FAO, as cited in Premium Times Nigeria, 2024, September 28). Federal Radio Corporation of Nigeria (FRCN). Nigeria Loses 50% of Agricultural Produce. https://.www.premiumtimesng.com/agriculture/agric-news/739762-nigeria-loses-50-of-agricultural-produce-post-harvest-fao.html., 2024.

[4] Ogundele, F. Post Harvest Losses and Food Security in Nigeria: An Empirical Review. African Journal of Agriculture and Food Science, 5(3), 77-89. https://abjournals.org/ajafs/papers/volume-5/issue-3/post-harvest-losses-and-food-security-innigeria-an-emperical-review/, 2022.

[5] United Nations Environment Programme. Food Waste Index Report, Nairobi. https://www.unep.org/resources/report/food-waste-index-report-2024, 2024.

[6] Centre for Renewable and Sustainable Energy Studies. Biomass Energy Science and Technology Department, Republic of South Africa. P2–3. https://www.crses.sun.ac.za/, 2018.

[7] Olarewaju, T. A., Oluwajimi, A. O., and Akerele, D. B. Bioenergy Potentials in Nigeria. In Proceedings of the 1st International Conference on Advances in Engineering and Technology (ICAET), 2019.

[8] Julliet B., Vasilije M., Philip L. Biomass Resources and Biofuels Potential for the Production of Transportation Fuels in Nigeria. Renewable and Sustainable Energy Reviews. P2, 2016.

[9] Octopus Energy. When will fossil fuels run out? Retrieved from https://www.octopus.energy/blog/when-will-fossil-fuels-run-out/, (2022, December 12).

[10] Meegle. Eco-Friendly Energy. Retrieved from https://www.meegle.com/en_us/topics/sustainable-energy/eco-friendly-energy,. 2025, January 17.

[11] Salem, M. Possibility of Utilizing Agriculture Biomass as a Renewable and Sustainable Energy Source. Heliyo. P2, 2022.

[12] Getu, M. E., Abebe, B. A., Midekssa, M. J., Araya, G. T., Amare, E. W. and Fedi, G. B. Briquette production from sugar cane bagasse and its potential as clean source of energy, 2021.

[13] Maung Y. M., Win, T.T, and Oo, A.T (2015). Preparation and characterization of bagasse ash. International Journal of Technical Research and Applications 3(1):84-87. https://www.ijtra.com/view/preparation-and-characterization-of-bagasse-ash.pdf, 2015.

[14] Abdulazeez. Crop Residue Yield Based on FAO crop production report in Nigeria. Nigerian journal of Animal Production, 593-542. https://njap.org.ng/index.php/njap/article/view/4932, 2024.

[15] Cha, J. S., Hoon, S., Jung, S., Ryu, C., Jeon, J., Shin, M. and Park, Y. Production and utilization of biochar: A review', *Journal of Industrial and Engineering Chemistry*, 40, pp. 1–3, 2016

[16] Rezaee, A., Ramin, M., Ghnizadeh, G. and AfsFhin, N.-A. 'Adsorption of Escherichia coli Using Bone Char', *J. Appl. Sci. Environ. Manage.*, 15, pp. 57–62, 2011.

[17] Adie, D. B., Lukman, S. and Yahaya, I. 'Comparative Analysis of Filtration Using Corn Cob , Bone Char and Wood Chippings', 3(3), pp. 146–152, 2013.

[18] Ahmed, M. B., Zhou, J. L., Ngo, H. H. and Guo, W. *Insight into biochar properties and its cost analysis*, 2007.

[19] Sevilla, M. and Fuertes, A. B. 'The production of carbon materials by hydrothermal carbonisation of cellulose', *Carbon*, 47(9), pp. 2281–2289. doi: 10.1016/j.carbon.2009.04.026. 2009.

[20] Kumar, A.. Jones, D. D., and Hanna, M. A. Thermochemical Biomass Gasification: A Review of the Current State of the Art. Industrial and Engineering Chemistry Research, 48(19), 8973-8991. Doi:10.1021/ie900078w

[21] Kambo, H. S. and Dutta, A. A Comprehensive Review of biochar and Hydrochar in Terms of Production, Physico-chemical Properties and Applications Renewable and Sustainable Energy Reviews. P359-378, 2015.

[22] Lohri, C. R., Sweeney, D., Rajabu, H. M. Carbonising Urban Bio-waste for Low-cost Car Production in Developing Countries: A review of knowledge, practices and technologies. University of De res Salam Tanzania, 2015.

[23] Suriya C., Eimsa-ard, S. Promvonge, P. Chuwattanakul, V. Rice Husk Combustion Characteristics in a Rectangular Fluidized-bed Combustor with Triple Pair of Chevro-shaped Discrete Rubbed Walks. Case Studies in Thermal Engineering: ScienceDirect p1., 2019.

[24] Elena C., Marina L., and Valerie M.. Hydrothermal Carbonisation of Microalgal Biomass: An Eco-Sustainable process to improve Properties and Effectiveness of Microalgae in Different Applications. Marco Montovani p1-3.

[25] Shekhar N. Popularization of biomass briquettes-A means for sustainable rural development. Asian Journal of Management Research 2(1):457-473, 2011.

[26] Titirici, M. M., Thomas, A., Yu, S. H., Muller, J. O. and Antonietti, M. 'A direct synthesis of mesoporous carbons with bicontinuous pore morphology from crude plant material by hydrothermal carbonisation', *J. Chem. of Mater.*, 19(17), pp. 4205–4212. doi: 10.1021/cm0707408, 2007.

[27] Danso-Boateng, E., Holdich, R. G., Wheatley, A. D. and Martin, S. J. 'Hydrothermal Carbonization of Primary Sewage Sludge and Synthetic Faeces : Effect of Reaction Temperature and Time on Filterability', *AlChE Journal*, 34(5), pp. 1279–1290. doi: 10.1002/ep., 2015

[28] Libra, J. A., Ro, K. S., Kammann, C., Funke, A., Berge, N., Neubauer, Y., Titirici, M., Fühner, C., Bens, O., Kern, J. and Emmerich, K. 'Hydrothermal carbonization of biomass residuals: A comparative review of the chemistry, processes and applications of wet and dry pyrolysis', *Biofuels*, 2(1), pp. 89–124, 2011.

[29] Gupta, D., Mahajani, S.M., Garg, A. Investigation on hydrochar and macromolecules recovery opportunities from food waste after hydrothermal carbonisation. Sci. Total Environ. 2020, 749, 142294.

[30] Azaare, R. R.., Okpoti, S., Addo, A., Antwi-Danso, S. K., and Appiah, T. E. Co-hydrothermal carbonization of pineaaple and Watermelon peels: Effect of process parametrs on hydrochar yield and energy content. Frontier Studies in Soil Science, 2021. https://www.researchgate.net/publication/351831624 Co-hydrothermal carbonization of pineapple and watermelon peels Effect of process parameters on hydrochar yield and energy content

[31] Van der Gaag, P. K. J. "Hydrothermal carbonisation of fruit peels, "Renew. Energy, vol. 15, no. 3, pp. 200-210, 2023.

[32] Olorunnisola, A. O. Investigating African locust bean pods as a sustainable biomass binder. *Renewable Energy*, 117, 422-431, 2018.

[33] ASTM D4442-07: Standard Test Methods for Direct Moisture Content Measurement of Wood and Wood-Based Materials, 2007.
[34] CEN/TS 14775: Solid biofuels – Method for the determination of ash content. European Committee for Standardization, 2004.
[35] ISO 3131: Wood-Determination of Density for Physical and Mechanical Tests. International Standardization Organization, 1975.
[36] ISO 616:2021, ˝Coke-Determination of Shatter Indices, ˝International Organization for Standardization, 2021.
[37] ASTM F22-13 (Reapproved 2021), ˝Standard Test Method for Hydrophobic Surface Films by the Water-Break Test,˝ ASTM International, West Conshohocken, PA, 2021.
[38] ASTM E1354-24 ˝Standard Test Method for Heat and Visible Smoke Release Rates for Materials and Products using an Oxygen Consumption Calorimeter. ASTM International, West Conshohocken, PA, 2024.
[39] ASTM D-5865-95˝Standard Test Method for Gross Calorific Value of Coal and Coke. West Conshohocken, PA, ASTM International, 1995.
[40] Onukak, I. E., Mohammed-Dabo, I. A., Ameh, A. O., Okoduwa, S. I., Fasanya, O. Production and characterization of biomass briquettes from tannery solid waste. Recycling 2(4):1-19, 2017.

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