Physicomechanical and fuel properties of sawdust briquettes using *Abelmoschus esculentus* waste as a binder

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Abstract: Various physicomechanical and fuel properties of sawdust briquettes with *Abelmoschus esculentus*(okra)*waste* binder additive were determined. Elemental analysis was done to determine the Oxygen(O), hydrogen (H), and Carbon content of the briquettes. Volatile matter, ash content, fixed carbon, heating value, density, compressive strength, stability, durability, and shatter resistance. The 5%, 10%, 15%, and 20% *Abelmoschus esculentus* composition *per* weight were used. The 5% Okra briquette had the highest volatile matter and heating value of 85.46% and 17,820 kJ kg^{-1}, while maintaining the lowest ash content and moisture content of 1.59% and 7.6%, respectively. The briquette with 5% Abelmoschus esculentus (Okra) composition had the highest Carbon (C), Hydrogen(H), and Oxygen (O) contents of 42.70%, 5.64%, and 42.76%, respectively. The results were within international standard limits for briquettes. Based on the results obtained, the sawdust-*Abelmoschus esculentus*briquette can adequately replace firewood in sub-Saharan Africa. Okra showed great potential as a binder with a very high hardness level of 7 hours in the water without disintegration. Increased utilization of agro-wastes briquettes will ensue while carbon emissions from the open burning of wastes will reduce. Equally, the use of clean cookstoves will increase with the production of these briquettes and will lead to a reduction in the present rate of deforestation that will result from domestic heating processes.

Keywords: abelmoschus esculentus, briquette, specific fuel consumption, binder, biomass

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1 Introduction

While current global environmental conditions have made finding alternatives to fossil fuels a worthwhile endeavour, excessive use of fossil energy has contributed to global warming and climate change. About 85% of the annual greenhouse gases emission come from fossil energy use (Huang et al., 2018). On the other hand, biomass is a renewable resource compared with fossil energy, making biomass a good substitute for fossil fuel. On the other hand, Biomass is a carbon-neutral renewable energy source containing chemical fuels from living organisms or their metabolites. It includes agricultural and food processing wastes and energy plants. Moreover, biomass is highly available and, when used appropriately, does not lead to environmental degradation, thereby making it sustainable (Muhammad et al., 2019) as it occurs globally in diverse forms.

Inadequate energy provision, especially for rural households, is a significant challenge of developing

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countries, leading to over-dependence on firewood for cooking with its consequent health and environmental hazards (Osei et al., 2020). Whereas vast quantities of waste biomass residues with cooking fuel potentials are available, women spend more than 6 hours daily collecting and preparing fuelwood in some regions of many developing countries. Moreover, of all alternatives to fossil fuels, biomass is the only carbon-based energy resource. Minimal changes are, therefore, required for biomass deployment in conventional energy harnessing equipment. Besides, its variety and global spread give biomass global significance in energy sustainability.

According to the World Bank Organization (2015), 52% of Nigeria's 182.2 million-population are in rural areas and cook mostly with kerosene (fossil fuel), charcoal, and firewood. Firewood and charcoal use account for the loss of three percent of the country's forest cover annually (ITTO, 2008). Wood and charcoal emit pollutants like particulate matter (especially those greater than 2.5 μg m^{-3}), Carbon Monoxide, Carbon Dioxide, Nitrogen Dioxide, Formaldehyde, and polycyclic organic matter like benzopyrene, and carcinogens. These harmful substances cause known health hazards (WHO, 2016). It is, therefore, necessary to transit to a more sustainable form of energy that is locally available and less hazardous.

Biomass briquetting compresses loose materials like waste sawdust, chips, shavings, agricultural waste, and other biomass materials under high pressure and temperature that softens the lignin content and binds the material into a cohesive, stable briquette. Adventitious organic or inorganic binding agents can also be used. Briquetting improves the utility of loose biomass materials as fuel (Tumuluru, 2010). However, the carcinogenic nature of the smoke of some inorganic binders, *among other things,* is of grave concern to its use. In contrast, the widespread use of organic binders like plant extracts is hindered by the availability of raw materials. It is thus necessary to discover more locally available organic binders for sustainable and environmentally friendly biomass briquettes.

Okra **(***Abelmoschus esculentus***)** is a local plant of African origin and exists in countries like Nigeria, Cameroon, Ghana, Pakistan, Iraq, and India. It is used as a local soup ingredient and a binder for drug tablet formation (Biswajit, 2014). Okra is a suitable food for diabetic, ulcer, and high blood pressure-prone individuals (Chanchal et al., 2018). Much waste from okra is often seen in Nigerian markets, farms, and homes due to limited use: it is not seriously preserved. It is a multi-cellular fiber with 67.5% a-cellulose, 15.4% hemicelluloses, 7.1% lignin, 3.4% pectic matter, 3.9% fatty and waxy matters, 7.45% carbohydrate and 2.7% aqueous extract. The heating value of 16,114 kJ kg^{-1} exceeds that of many other binder materials: cow dung (12,830 kJ kg^{-1}), gum Arabic (8,368 kJ kg^{-1}), molasses (7,000 – 10,000 kJ kg^{-1}), neem leaves (4,520 kJ kg^{-1}) and clay (2,589 kJ kg^{-1}) (USFDA database). Whereas cassava starch has a higher heating value (17,484 kJ kg^{-1}), its 40.6%-90.77% starch content, is compared to okra's 7.45% carbohydrate (Zhou et al., 2007), makes it a less environmentally friendly binder.

The objectives of this study were to evaluate the potential of waste from okra, a local plant as a binder for sawdust briquette production, to determine the physical, mechanical, and elemental properties of the briquettes produced and to compare them with that of other briquettes.

2. Materials and methods

2.1 Selection of raw materials

Sawdust and a binder (okra waste), see Figure 1, were used in the study. Sawdust is highly available, and its present local open-air burning-disposal method causes environmental emission problems. The okra's 7% carbohydrate (Okedere, 2017) will translate to low greenhouse gases emission during combustion. Equally, its mucilage has been reported as a binder for tablet production. It is highly available in the local communities, and the decay of the used ones pollutes the environment.

(a) sawdust (b) dried waste (*Abelmoschus esculentus*)

Figure 1 The briquette raw materials

2.2 Preparation of biomass

The 100 kg of sawdust was collected from a wood processing mill at Nsukka (Latitude 6°51′24″N and Longitude 7°23′45″E), Enugu State, Nigeria. After that, it was milled and graded with a (Haver and Boeker, Germany) digital sieve shaker number 59302 OELDE into 1,000 μm, 500 μm, 300 μm, and 212 μm particle sizes. The okra waste was collected (free of charge)from farmers and market women in the area, sun-dried to 12.6% moisture content, and milled to a 212 μm particle size (Table 1).

Table 1 The Briquette CompositionMix

Sawdust Concentration		*Abelmoschus esculentus*Concentration		
Quantity (g)	Particle Size (μm)	Quantity (g)	Proportion (% of Saw Dust)	Particle Size (μm)
500	1,000	25	5	212
500	500	50	10	212
500	300	75	15	212
500	212	100	20	212

2.3 Preparation of briquettes

The 500 g of each particle size(1000 μm, 500 μm, 300 μm, and 212 μm)of the milled sawdust was weighed out with a 0.001 g sensitivity digital balance and combined with different proportions of the okra;5%, 10%, 15%, and 20% of the sawdust weight. After that, each composition was mixed thoroughly with 300 cm^3 of water, and fed into a manual cylindrical hydraulic briquette press and compressed to a pressure of 25 MPa. Finally, the briquettes were sun-dried for 48 hours in a solar dryer at a mean temperature of 55.6^{o}C to 0.10% moisture content. The briquette was stored in lab, in the open under atmospheric conditions. The produced briquettes are shown in Figure 2. For each mixture, nine (9) briquettes were made, amounting to 144 briquettes.

Figure 2 The Sawdust-*Abelmoschus esculentus* Briquettes

2.4 Experimental setup

For each particle size and okra concentration, the production was replicated three times. In other words, A, B, C, D are the okra concentrations of 5%, 10%, 15%, and 20%, respectively, while 1, 2, 3, and 4 are the particle sizes of 1000 μm, 500 μm, 300 μm, and 212 μm, respectively. From this setup, there are 16 analysis points; these points were replicated 3 times, thus making up a total of 16 × 3 experimental points that amount to 48 experiments. Therefore, the total number of briquettes that were produced amounted to 48 briquettes.

2.5 Proximate analysis of biomass

Proximate analysis of the briquette, including moisture content, volatile matter, ash content, and fixed carbon, were determined using standard procedure.

Percentage volatile matter (%VM): The volatile matter was determined by ASTM (2013). 200 grams of briquettes were dried in an oven at 105°C for one hour and later heated in the furnace at 550°C for 10 minutes. The residue was reweighed after cooling, and the percentage of volatile matter determined using Equation 1.

$$\%VM = \frac{X-Y}{G} \times 100 \quad (\%) \qquad (1)$$

Where:

G = initial weight of sample, g

X = weight of dry matter, g (after oven drying)

Y = weight of residue, g.

Ash content: The amount of the incombustible material remaining after burning the briquette sample was determined by ASTM (2013) as percentage ash content(%ash). See Equation 2. The 200 grams of the briquette was heated in the furnace at 550°C for 4 hours, and the residue reweighed after cooling.

$$\%ash = \frac{S}{G} \times 100 \quad (\%) \qquad (2)$$

Where: S = weight of ash residue, g.

Moisture Content: Based on ASTM (2013), 200 grams of the sample was kept in an oven at 105 ℃ for one hour, and the percentage moisture content dry basis**(**%MC**)** was calculated using Equation 3.

$$\%MC = \frac{G-X}{G} \times 100 \quad (\%) \qquad (3)$$

Percentage fixed carbon(%FC): The solid combustible residue that remains after expelling the volatile matter from the briquette was evaluated as in Equation 4.

$$\%FC = 100 - (\%VM + \%ash + \%MC) \; (\%) \qquad (4)$$

2.6 Physico-mechanical properties

The physical, mechanical, and fuel properties of the briquettes determined included density, stability (axial and lateral), compressive strength, hardness, shatter resistance, tumbling/durability, thermal efficiency, specific fuel consumption, and heating value.

Shatter resistance: The hardness of the briquettes was determined by dropping briquettes of known weight and length from 1 m height to a concrete floor ten times. First, the weight of the disintegrated briquette was read, and the material loss (%WL) was calculated using Equation 5 (Madhava et al., 2012). Next, the percentage of shatter resistance (%SR) was evaluated using Equation 6.

$$\%WL = \frac{W_1-W_2}{W_1} \times 100 \quad (\%) \qquad (5)$$

$$\%SR = 100 - \%WL \quad (\%) \qquad (6)$$

Where:

W_1 = weight of briquette before shattering, g

W_2 = weight of briquette after shattering, g

$\%WL$ = percentage weight loss,%.

Durability/Tumbling resistance (%TR): This test was done according to British Standards for fuels: EN 15210-1 (2009) using a sieve shaker. Briquettes sample of known weight was put in the sieve and covered with a lid, and was thoroughly shaken for 15 minutes. The weight loss in the briquettes was noted, and the tumbling resistance was calculated by using Equation 8 (Tayade et al., 2010).

$$\%\,weight\ loss = \frac{W_3-W_4}{W_3} \times 100 \quad (\%) \qquad (7)$$

$$\%TR = 100 - \%\,weight\ loss \quad (\%) \qquad (8)$$

Where:

W_3 = weight of briquette before tumbling, g

W_4 = weight of briquette after tumbling, g

Stability: Briquettes stability was determined as the percentage expansion in length (lateral) and diameter (axial) of samples at 96 hours after removing the pressing mould, from the measurements immediately after removal. Measurements were taken at three points on each briquette using Digital Vernier calliper and the average selected.

$$\%\,increase\ in\ length = \frac{L_F - L_O}{L_O} \times 100 \quad (\%) \quad (9)$$

Where:

L_o = Length of briquette immediately after removal from the mould, mm

L_f= Length of briquette 96 hours after removal from the mould, mm

$$\%\,increase\ in\ diameter = \frac{D_F - D_O}{D_O} \times 100 \; (\%) \; (10)$$

Where:

D_o = Diameter of briquette immediately after removal from the mould, mm

D_f= Diameter of briquette 96 hours after removal from the mould, mm.

Compressive strength (CS): This was determined using number 8889 Hounsfield tensometer following ASTM D143–2008 (De La Cruz et al., 2020), M for only compact and intact briquettes. The briquette sample was placed horizontally in the compression test fixture and loaded until the briquette failed by cracking or breaking. The maximum load that fractured the briquette was recorded. The strength was evaluated with Equation 11 in N mm^{-1}.

$$CS = \frac{3 \times fracture\ point\ load\ (N)}{L_1 + L_2 + L_3} \quad \text{N mm}^{-1} \qquad (11)$$

Where:

L_1= Length of briquette at point 1, mm

L_2= Length of briquette at point 2, mm

L_3= Length of briquette at point 3, mm.

Density: The density of the briquettes was determined following ASTM D 2395-2008 (De La Cruz et al., 2020), 14 days after removal of briquettes from the press using Equation 12. The mass was measured with an electronic balance of 0.01 g-accuracy and the diameter and length with a Digital Vernier Caliper of 0.01 mm-accuracy.

$$Density = \frac{Weight\ of\ briquettes}{Volume\ of\ briquettes} (\text{kg m}^{-3}) \qquad (12)$$

Hardness: The hardness of the briquettes was measured using the German Standard DIN 5173 testing method. The briquettes were immersed into a water-filled container at room temperature, then the time for disintegration was read with a stopwatch. Briquettes with 5, 10, and 20 minutes disintegration time are graded as low, medium, and high-quality briquettes, respectively (Križan, 2007).

Heating Value (HV): The heat produced by the complete combustion of a unit quantity of the briquette was calculated in MJ kg^{-1} using Equation 13. It was determined with an adiabatic bomb calorimeter (ASTM, 2013). (Nhuchhen and Afzal, 2017).

$$HV = (0.0352 \times \%F_c + 0.1846 \times \%V_m)\ MJ\ kg^{-1} \qquad (13)$$

Where $\%F_c$ and $\%V_m$ are fixed carbon and volatile matter, respectively

Elemental Analysis

The importance of proximate analysis is its usefulness in the determination of the elemental composition of the briquettes. For energy materials, the three critical common elements are Carbon (C), Hydrogen (H), and Oxygen (O). Jigisha et al. (2007) gave Equations 14, 15, and 16, respectively, to estimate biomass elemental composition for Oxygen (C), Hydrogen (H), and Carbon (C) at a 95% confidence interval.

$$C = 0.637F_c + 0.455V_m \qquad (14)$$

$$H = 0.052F_c + 0.062V_m \qquad (15)$$

$$O = 0.304F_c + 0.476Vm \qquad (16)$$

Where C, H, and O are Carbon, Hydrogen, and Oxygen.

3 Results and discussion

3.1 Proximate analysis of briquette

The briquettes' volatile matter, ash content, moisture content on a percentage weight basis, fixed carbon, and heating value for the various briquette mixes are shown in Table 2.

Table 2 Proximate analysis of the briquettes

Binder Conc. per Sawdust Wt. (%)	% Volatile Matter (%)	% Ash Content (%)	% Moisture Content (%)	% Fixed Carbon (%)	Heating Value (HHV) (MJ kg^{-1})
5%	85.46±0.05^{d*}	1.59±0.01^{a*}	7.67±0.01^{a*}	5.28±0.01^{a}	17.82±1.09^{d*}
10%	84.20±0.04^{c}	1.85±0.01^{b}	8.00±0.01^{b}	5.87±0.01^{c}	17.61±0.71^{c}
15%	83.57±0.04^{b}	1.93±0.01^{c}	8.20±0.01^{c}	5.86±0.01^{b}	17.49±0.71^{b}
20%	83.30±0.04^{a}	2.10±0.01^{d}	8.50±0.01^{d}	6.25±0.02^{d*}	17.38±1.18^{a}

Note: Rank a denotes the lowest value, and d the highest, with * showing the most significance. Wt. = weight

Volatile matter: The volatile matter for these sawdust-okra briquettes were in the range of 83.30%–85.46%. The highest (85.46%) came from 5% okra briquette, while the least was from 20% okra briquette. These values were higher than 68.14% – 74.67% obtained by Jittabut (2015) for rice straw and sugar cane leaves briquettes having molasses binder, but lower than 83.06% obtained by Oladeji and Lucas (2014) for binder-less corn cob briquette. The volatile matter from this study was higher than that reported for coal; 41.12% and coal-rice husk briquette; 25.26% by Ikelle et al. (2014). Ajimotokan et al. (2019) noted that fuels' high volatile matter content translates to more excellent proportionate flame and ease of ignition. High volatile matter is an indication that the briquette is highly combustible.

Ash content: The ash content varied between 1.59% – 2.10%, with the 5% *Abelmoschus Esculentus* concentration briquette having the lowest, 1.59%, and the least possible tendency to slagging. In comparison, briquettes from rice husk with corn starch binder have 16.10% ash (Efomah and Gbabo, 2015), mango leaves, subabal leaves, and sawdust combination had 9.01% – 11.43% (Birwatkar et al., 2014) and15% and 35% cassava starch binders gave10.46% and 8.43%, respectively(Tembe et al., 2014). The ash content of briquettes affects its slagging b in conjunction with the ash's operating temperature and mineral composition. The ash contents of the 5%, 10% and 15% *Abelmoschus esculentus* concentration briquettes were within the ≤ 2% range recommended by the European standards (EN 14775) for woody biomass.

Moisture content: The moisture content was within the range of 7.67% – 8.50%. The highest was from the 20% *Abelmoschus esculentus* concentration briquette, while the lowest moisture content was from the 5% concentration briquette. The moisture content was less than that of the 12.67% reported by Efomah and Gbabo (2015) for rice husk briquettes and the 12.94% reported by Tembe et al. (2014) for briquettes produced from groundnut shells, rice husk, and sawdust using cassava starch as a binder. High moisture in biomass materials prevents their thermochemical conversion processes as the water content influences the net calorific value and the combustion efficiency and temperature. The British standard for briquettes, BioGen/UK Code of Good Practice and the European Briquette standard; EN 14961-1 specify a < 10% moisture content for briquettes; the *Abelmoschus esculentus* briquettes are within the limits (Hahn, 2004).

Fixed carbon: The fixed carbon composition; (the percentage of carbon available for char combustion) of the produced briquettes was in the range of 5.28%–6.10%. Murali et al. (2015) reported 11.87% fixed carbon for binderless sawdust briquettes, while Birwatkar et al. (2014) obtained 12.45% – 17.04% fixed carbon for mango leaves, subabal leaves, and sawdust briquettes. Jittabut (2015) got 9.06% – 13.63% for rice straw and sugar cane leaves briquettes having molasses as a binder. Ogwu et al. (2014) reported a fixed carbon content of 9.95% for sawdust particles of *Daniella Oliveri* and *AfzeliaAfricana* with cassava starch as a binder. It can be seen that these sawdust-*Abelmoschus Esculentus* briquettes were within the range.

Heating value: The sawdust-*Abelmoschus Esculentus* briquettes had a calorific value in the range of 17,820 – 17,380 kJ kg^{-1}, as shown in Table 2 and graphically illustrated in Figure 3. Its average heating value of 17,575 kJ kg^{-1} was comparable to that of firewood (16,000 kJ kg^{-1}) but lower than that of charcoal (29,500 kJ kg^{-1}) and kerosene (35,000 kJ kg^{-1}); reported by Islam et al. (2014). The 5% binder level had the highest calorific value, 17,820 kJ kg^{-1}, as seen in Figure 3. The heating values of the produced briquettes were greater than the ≥ 16,500 kJ kg^{-1} acceptable level of the European Briquette standard; EN 14961-1. Ajimotokan et al. (2019) reported that fuels with higher fixed carbon content and volatile matter exhibited high calorific values. The briquettes they produced from charcoal particles and pine sawdust having higher fixed carbon;44.6% – 48.3%compared to the 5.28% – 6.25% obtained from the present study showed high calorific values;19,400–24,900 kJ kg^{-1} as against the 17,820 – 17,380 kJ kg^{-1} from this study.

Generally, the 5% okra concentration-briquette gave the highest volatile matter- 85.46% ± 0.05% and calorific value- 17,820 ± 1,089 kJ kg^{-1}. It equally had the lowest ash content-1.59% ± 0.01%, fixed carbon-5.28% ± 0.01% and moisture content- 7.67% ± 0.01%. These results were comparable with those from other researchers.

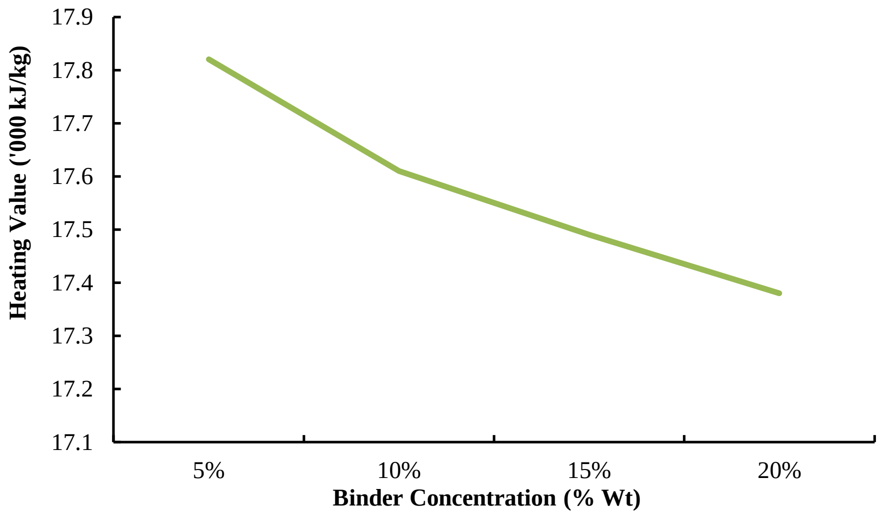

Figure 3 Variation of heating values for various binder concentrations

3.2 Elemental analysis

According to Obi and Okongwu (2016), the elemental composition of solid fuels affects their inherent heating value, hence their energy output. The higher the carbon content of the fuel, the significant the value of the heating value (HV). From Table 3, the carbon content of the briquettes was in the range of 42.7 to 41.76 Wt% for the okra binder level of 5 to 20 Wt%. The 5 Wt% sawdust-okra briquettes had the highest fixed carbon content of 42.7 Wt% due to the high composition of the sawdust in the mixture. From the result, it is understandable why the 5 Wt% briquette sample had the highest heating value (HV) of 17,820 kJ kg^{-1}. The Oxygen (O) content decreased with the increase in binder level of 5 to 20 Wt%. The result had a similar trend with Obi and Okongwu (2016) and Ajimotokan et al. (2019).

Table 3 Carbon, hydrogen, and oxygen compositions of the briquette samples

Sawdust/Okra Briquette	C (% Wt)	H (% Wt)	O (% Wt)
5%	42.70	5.64	42.76
10%	42.05	5.53	41.86
15%	41.76	5.49	41.56
20%	41.88	5.49	41.55

3.3 Physico-mechanical properties

Shatter resistance: High shatter resistance indicates that briquettes have high shock and impact resistance. As shown in Figure 4, the shatter resistance ranged from 96.78% to 98.92% and increased with decreasing particle size and increasing binder concentration. The briquettes produced by Birwatkar et al. (2014) from mango leaves, subabal leaves, and sawdust combination had average shatter resistance of 94.46%, which is lower than the 97.8% average of briquettes from this study. Tabil and Sokhansanj (1996) and Adapa et al. (2003) considered shatter resistance of > 80% as acceptable.

Tumbling resistance: This denotes the durability of briquettes. The briquettes tumbling resistance shown in Figure 5 revealed a maximum of 95.68% from the 212 μm sawdust particle *cum* 20% binderand a minimum of 93.58% from 1,000 μm sawdust - 5% binder briquettes. The Groundnut shell briquettes with starch as a binder from Oyelaran et al. (2015) had lower durability of 69.89% – 93.52%. The briquettes from this study were within the tumbling resistance of ≥ 90% recommended by Tayade et al. (2010) and close to ≥ 96.5% of the European Briquette standard EN 14961-1.

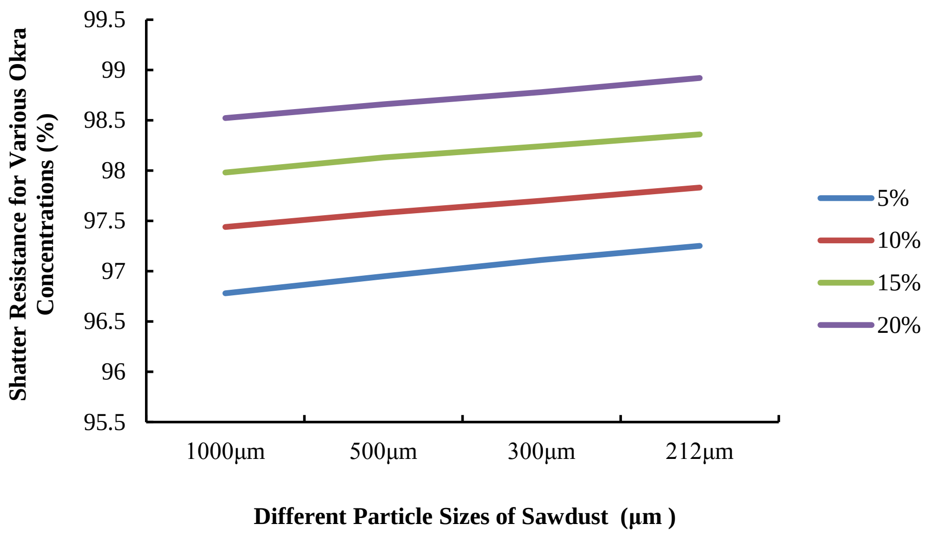

Figure 4 Shatter resistance for various binderconcentrations and particle sizes

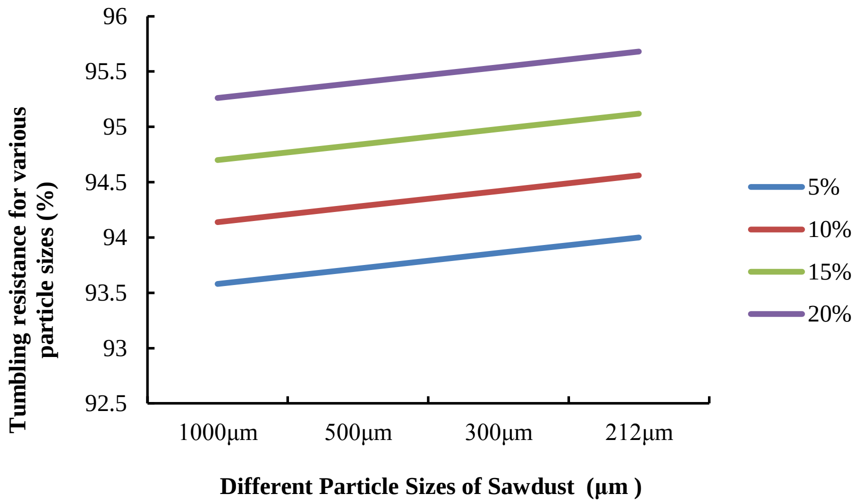

Figure 5 Briquette tumbling resistance result

Generally, the finest grade (212 µm) and the highest binder concentration (20%) briquettes are most resistant to disintegration that may result from handling and transportation perturbations. However, its volatile matter, ash and moisture contents, and calorific value were the least favourable.

Stability: This is an index of the resistance of briquettes to swelling after production; the less the change of lateral and axial dimensions, the more stable the product (Al-Widyan et al., 2002). The lateral and axial stability denotes the extension/increase in the briquettes' length and diameter. As seen from Figures 6 and 7, the average increase in the diameter and length was 0.26 mm and 1.01 mm, respectively, and is below groundnut shell briquettes with cassava starch binder (0.60 mm and 1.91 mm, respectively) (Oyelaran et al., 2015). Particle size affects stability; the minor change was witnessed in particle size of 212 µm sawdust having 20% binder concentration.

Density: As seen in Figure 8, **t**he density of the briquettes ranged from 570.34 – 626.45 kg m^{-3}. The density was higher than the 355 – 425 kg m^{-3} of charcoal grade briquettes having starch binder (Zubairu and Gana, 2014) and the mango leaves, subabal leaves and sawdust combination briquettes having a maximum density of 579.5 kg m^{-3} (Birwatkar et al., 2014). Jittabut (2015) got 530 – 580 kg m^{-3} density briquettes from rice straw and sugar cane leaves with molasses binder, while Oladeji (2004) produced binderless corn cob briquettes with a 650 kg m^{-3} maximum density. Higher density briquettes were obtained with finer sawdust particles and higher binder concentrations; this could be attributed to reduced void spaces that exist with smaller particle-sized bulk materials. The 212 µm *cum* 20% binder gave the highest density briquette; 626 kg m^{-3}. The 20% briquettes were within the ≥ 600 kg m^{-3} density recommended by the European standard; EN 14961-1, as suitable for cost-effective handling and transportation. The rest of the briquettes were less than this recommended density.

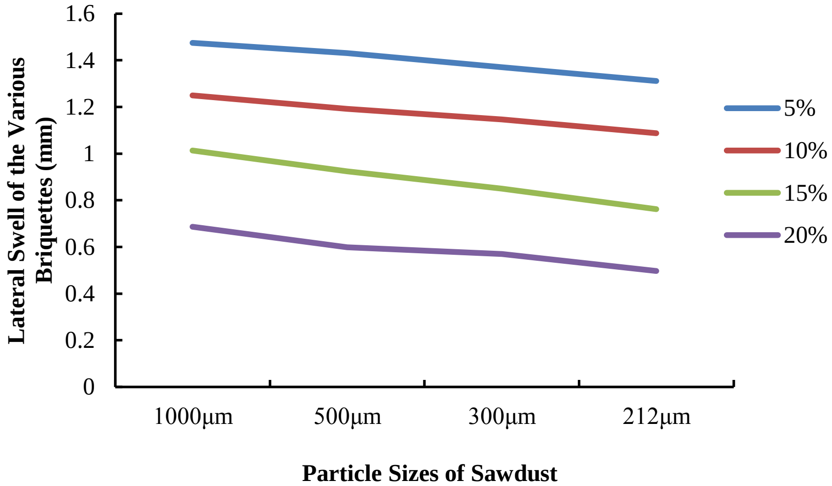

Figure 6 Briquette lateral stability result

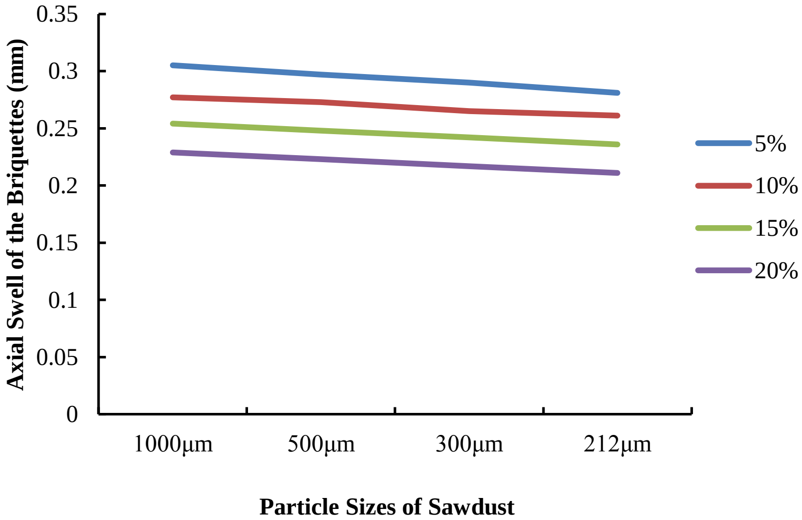

Figure 7 Axial resistance of briquettes

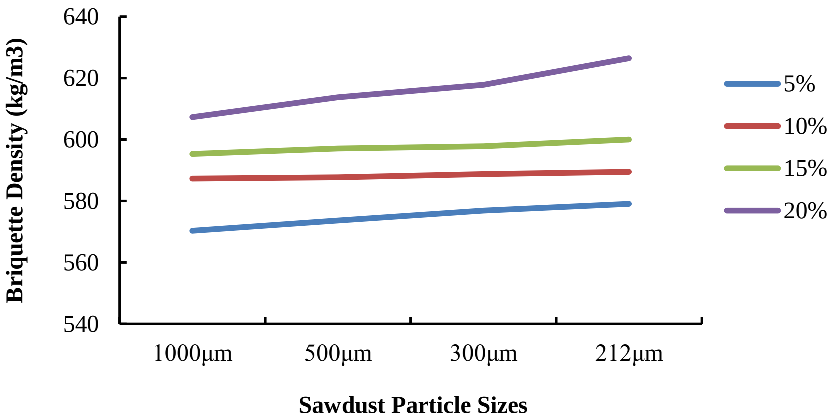

Figure 8 Bulk density of various particle sizes of briquettes

Hardness: According to Križan (2007), briquettes are categorized into low quality, medium, and high quality if it does not disintegrate when submerged in water for 5, 15, and 20 minutes. The produced briquettes were soaked in water (see Figure 9) for 7 hours (equivalent to 420 minutes) before they disintegrated, distinguishing them as having high quality.

Figure 9 Briquette hardness test

Compressive strength: As shown in Figure 10, the average compressive strength was 22.0 kN m^{-2} while the maximum was 31.0 kN m^{-2} and was higher than the 2.34 kN m^{-2} maximum compressive strength for binderless corn cob briquettes of Oladeji et al. (2004). A 1.969 kN m^{-2} briquette strength is considered adequate for withstanding handling disturbances (Plistil et al., 2005); the briquettes from this study met this standard. Whereas the 5% binder briquette exhibited the comparatively highest strength at the 212 μm particle size and lowest at the 1,000 μm particle size, the 15% one had the lowest strength at the 212 μm particle size, but highest at the 1,000 μm. Particle size affected compressive strength, which generally increased with decreasing particle size, with a wavy trend. Bulk material with smaller particle sizes has a lower void ratio and inter-particular distances; consequently, higher adhesive forces may be expected. Thakur et al. (2014) reported that coarse particle agglomerates exhibit less strength in resisting deformation as an increase in adhesive contact would result from increased surface areas of finer particles. The compressive strength was higher for the 5% and 20% binder concentrations but lower for the intermediate ones, especially at smaller particle sizes.

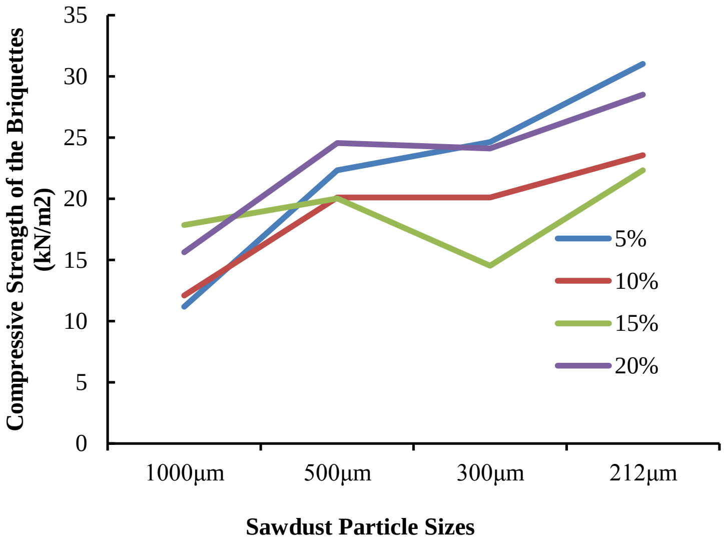

Figure 10 Compressive strength results

3.4 Significance and potential implications of the results

Bentsen et al. (2014) estimated the theoretical global primary agricultural biomass potential to be 3.79 metric tonnes of dry matter annually. This biomass includes the massive agro-residues that abound, especially in developing economies like Nigeria that need to be harnessed. One of the critical problems facing briquettes use as an alternative cooking energy source is a suitable organic binder for its production. The study has shown Okra (*Abelmoschus esculentus*) as a suitable briquette binder. If fully utilized, rural communities in Sub-Saharan Africa and Nigeria can depend on briquettes as an alternative to firewood in cooking and other heating purposes with the availability of modern, clean cookstoves. This will also aid in the reduction of deforestation due to firewood and charcoal use.

A strong partnership should be developed with the non-governmental organization, for example, the Alliance for Clean Cookstoves. Utilizing these biomass wastes helps in reducing the pollution from developing countries due to inappropriate biomass waste disposal. In communities that produce rice husk, these energy materials are used as an alternative energy source for heating needs in the rural areas, thus ensuring energy justice in the energy, food, and water nexus.

4 Conclusion

The above results have highlighted the high potentials of briquettes production from sawdust using okra as a binder for domestic and industrial heating applications. It also confirms the vital role of particle size on various physio-mechanical properties of the sawdust-okra briquettes, such as compressive strength, density, shatter resistance, tumbling resistance, and lateral and axial stability.

The elemental composition of the sawdust briquettes bonded with okra showed that 5% of binder level had the highest fixed carbon and oxygen content with values of 42.7 and 42.76 wt, respectively. The 5% sawdust-okra briquette sample exhibited a very significant hardness level with a value of 2,85 kN m^{-2}.

Extensive research in the use of okra mucilage as a potential binder is necessary to validate its viability in producing press-type briquettes.

Conflict of Interest

The authors declare no conflict of interest.

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