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High-Performance Pineapple Leaf Briquettes Using Cassava Starch and Okra Mucilage Binders: Combustion, Fuel Quality, and Mechanical Characterization

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ABSTRACT

Due to the dual crisis of energy poverty and waste management, there is a need to harness biomass-solid-based energy from agricultural waste to improve energy access and enhance waste management, especially in Sub-Saharan Africa. This study investigated the feasibility of producing briquettes from pineapple leaves using starch and okra mucilage binders. Proximate analysis, burning test, elemental analysis, and mechanical test were done. The binder concentrations used were 5%, 15%, 25%, and 35%. Results revealed that 25% okra binder briquettes performed better, with 76.58% volatile matter, 29.13 MJ/kg heating value, 3.57% moisture content, 41.30% carbon, 5.27% hydrogen, and 39.53% oxygen, of which all met the recommended standard. The heating value for the remaining concentrations (26.09-28.84 MJ/kg) all met the international standard. Also, the mechanical tests—density (581.63-750.14 kg/m³), shatter resistance (96.01%-99.96%), tumbling resistance (92.07% to 99.62%), compressive strength (7251.6-8886.2 KN/m²), and water resistance (exceeding 1080 minutes)—for all the binder concentrations were within the recommended international standard of briquettes. This ensures mechanical stability during handling and transportation. The findings revealed that pineapple leaves have significant potential as an alternative biomass source for briquette production capable of mitigating energy poverty in low-income countries.

Keywords: Pineapple, energy, briquette, biomass, binder, Abelmoschus esculentus.

1 INTRODUCTION

The contemporary state of the global energy sector is attributed to the accessibility, affordability, and sustainability crisis. This crisis is being faced concurrently with an imminent agricultural waste management crisis. Contrary to the fact that 92% of the global communities have access to electricity, more than 750 million people do not have access to electricity, and above 2 billion people depend on conventional solid fuels, that is, firewood, charcoal, and agricultural waste, for cooking and heating purposes (International Energy Agency, 2024). This energy poverty is severe in Sub-Saharan Africa (SSA), which houses 85% of the world's people who do not have access to electricity (International Energy Agency, 2024). Notably, intensified deforestation and land degradation, as well as indoor air pollution, will continue in a cyclic pattern due to the underutilization of agricultural wastes.

Valorization of agricultural residues presents opportunities to combat the dual crisis of energy poverty and waste mismanagement. The pineapple sector globally, which produces 28 million tons each year (Firățoiu et al., 2021), contributes significantly to the agricultural waste generated. In sub-Saharan Africa, countries such as Nigeria produce 1.6 million tonnes; Benin, Kenya, Tanzania, and South Africa, among others, are also contributing significantly to this sector (Food and Agriculture Organization

of the United Nations, 2023). Pineapple post-harvest waste and processing waste leaves are often disposed of or set on fire, resulting in poor waste management (Baidhe et al., 2021). More importantly, Zainuddin et al. (2014) cited that each pineapple plant bears “40 leaves each leaf weighing 0.065kg”, a total of 2.6kg of leaves per pineapple plant, with an average fruit weighing approximately 1.44 kg, yielding the ratio of leaves to fruit for every pineapple fruit produced of 1.81:1. This means that on annual global pineapple production, approximately 51 million tons of pineapple leaves are generated.

Biomass briquetting, a well-established technology for compressing loose residues into solid fuels, has gained attention from researchers and various government agencies worldwide due to the urgent need for a green transition. However, numerous studies across SSA have focused on briquettes made from sawdust, palm kernel, and other types of peels. A thorough literature review revealed that no research has used pineapple leaves as biomass for briquette production in SSA. Additionally, previous research on binders has primarily centered on starch, with only a few studies exploring okra as a binder for briquettes.

Therefore, it must be noted that despite the briquetting potential of any biomass, the binder choice and its nature greatly affect the briquette performance. Although it has been established that using cassava starch as a briquette binder is beneficial due to its ability to gelatinize (Zhou et al., 2007), research into other reduced-cost binder materials with good performance is important for the long-term success of the technology. One natural material that is promising but under-explored as a briquette binder is okra or “Abelmoschus esculentus” mucilage. Okra has many “polysaccharides” that can work well for binding; however, its effectiveness for briquetting, compared with cassava starch and other binders, has rarely been studied. Therefore, this research fills this critical gap by characterizing fuel briquettes produced from pineapple leaves. Specifically, this research seeks to:

I. Produce pineapple leaf briquettes using cassava starch and okra mucilage binders at several binder concentrations (5%, 15%, 25%, 35%).
II. Compare their combustion and physico-mechanical properties.
III. Determine the most desirable form and strength of binder to achieve fuel quality and mechanical strength as set by global standards.

The originality of this research work lies in the dual nature of its contribution: (1) It offers the very first evaluation of pineapple leaves for briquette fuel preparation, and (2) it offers a groundbreaking comparison between okra mucilage and cassava starch as binders.

2 MATERIALS AND METHODS

2.1 Raw Materials Selection

Pineapple leaves (see **Figure 1)** were used in the study. Pineapple leaves are highly available. Its underutilization results in open-air disposal and burning. Okra contains 7.45% carbohydrate, whereas cassava contains 40.6%-90.77% starch (Zhou et al., 2007). This makes them emit low greenhouse gases during combustion (Ohagwu et al., 2022). They are highly available in the local communities.



Figure 1: Pineapple waste preparation

2.2 Pineapple Waste Preparation

Pineapple leaves were collected from Nsukka (Latitude $6^{\circ}51'24^{"}N$ and Longitude $7^{\circ}23'45^{"}E$), Enugu State, Nigeria. The pineapple leaves were cut into smaller pieces for easy drying and grinding. They were both sun-dried and then, later, oven-dried for 48 hours, maintained at a temperature of 105℃, and later milled, amounting to 20 kg. After milling, it was sieved manually using a Test sieve (DIN ISO 3310-1, NF ISO 3310-1, BS 410-1, Aperture width =300 μm, sieve diameter =200mm, Serial-No.: 20165046, Haver and Boecker OHG D-59302 OELDE Made in Germany) to have a uniform particle size of 300 μm. Cassava (starch) was bought in powder form from Ogige market, Nsukka. Okra was bought from Ogige market, Nsukka, sun-dried for 4 days, and milled. **Figure 2** shows dried pineapple leaves, ground pineapple leaves, ground okra, and starch.



Figure 2: Dried pineapple leaves, milling process, milled leaves, and binders (okra and starch)

2.3 The Briquetting Process

A constant 300g mixture of sieved milled pineapple waste and ground okra binder was weighed using a 0.001g digital balance at different ratios of biomass-to-binder concentrations; 95%:5%, 85%:15%, 75%:25%, and 65%:35%. Then, each mixture was mixed thoroughly with $300cm^3$ of water, and fed into a manual cylindrical hydraulic briquette press, and compressed at a pressure of 25 MPa using a 20-ton hydraulic jack. The above process was repeated for the starch binder. **Figure 3** shows the produced briquettes**.** The briquettes were open sun-dried for 3 days and kept in the laboratory at room temperature.



Figure 3: Briquettes produced

2.4 Experimental Setup

For each mixture above, the production was replicated four times. There were 10 analysis points. These points were replicated three times for each mixture, yielding a total of (10 × 3) analysis points, hence 30 experiments per mixture. Okra binder had (30×4) experiments, and starch binder had (30×4) experiments because each binder had 4 mixtures (at 5%, 15%, 25%, and 35%). Therefore, a total of 240 briquettes were produced. This design helped to inform the actual number of briquettes to be produced, enough to carry out all the physico-mechanical and combustion tests in the subsequent sections.

2.5 Physico-mechanical properties

The physical and mechanical properties of briquettes determined included compaction ratio, compressed density, relaxed density, relaxation ratio, shatter resistance, durability/tumbling resistance, stability, hardness, and compressive strength.

2.5.1 Density

The density of the briquette was determined using ASTM D 2395-2008 (De La Cruz et al., 2020), 14 days after removal of briquettes from the press using Equation (2.1). The mass was measured using a digital balance of 0.01 g accuracy, and the diameter and length were measured using a digital vernier caliper of 0.01 mm accuracy.

$$D = \frac{mass\ of\ briquettes}{Volume\ of\ briquettes} \quad (kgm^{-3}) \qquad (2.1)$$

2.5.2 Shatter Resistance

Method by Ohagwu et al. (2022) was used. The hardness of the briquettes was determined by dropping briquettes of known weight from 1 meter to a concrete floor ten (10) times. The weight of the disintegrated briquette was read, and the weight lost (%WL) was calculated using Equation (2.2) (Madhava et al., 2012). Then, the percentage of shatter resistance (%SR) was obtained using Equation (2.3) (Ohagwu et al., 2022)

$$\%WL = \frac{W_1 - W_2}{W_1} \times 100 \quad (\%) \qquad (2.2)$$

$$\%SR = 100 - \%WL \qquad (2.3)$$

2.5.3 Durability/Tumbling Resistance (%TR)

It was determined using a sieve shaker according to the British Standards for fuels: EN 15210-1 (2009). A sample of a known weight of briquette was put in the sieve and covered with a lid, and was thoroughly shaken for 15 minutes. The weight loss in the briquette was calculated using Equation (2.4) (Ohagwu et al., 2022) and tumbling calculated using Equation (2.5) (Tayade et al., 2010).

$$\%weight\ loss = \frac{W_3 - W_4}{W_3} \times 100 \quad (\%) \qquad (2.4)$$

$$\%TR = 100 - \%weight\ loss\ (\%) \qquad (2.5)$$

Where:

W_3 =weight of briquette before tumbling, g

W_4 =weight of briquette after tumbling, g

2.5.4 Water Resistance

The German Standard DIN 5173 testing method was used to measure the hardness of the briquettes. The briquettes were immersed in a water-filled container at room

temperature. The time for disintegration was read using a stopwatch. Briquettes with 5-, 10-, and 20-minute disintegration time are graded as low, medium, and high-quality briquettes, respectively(Križan, 2007).

2.5.5 Compressive Strength (CS)

This was determined using Testometric testometric serial number 52978, type: DBBMTCL-1.5-000, Rochdale, England, www.testometric.co.uk. The briquette sample was placed vertically in the compression test fixture (see **Figure 4)** and loaded until the briquette failed by cracking or breaking. The maximum load that fractured the briquette was recorded. The strength was evaluated using Equation (2.6) in KNm^2.

$$CS = \frac{Maximum\ load\ that\ fractured\ the\ briquette\ (KN)}{Area} \quad (KNm^2) \qquad (2.6)$$



Figure 4: Compressive strength analysis

2.6 Combustion Test

2.6.1 Burning Rate

This is the rate at which a specific mass of fuel burns over a given time. A known mass of briquette was ignited using a gas flame from a gas cylinder. The stop clock was started at the same time, and stopped when the briquette was completely burnt. The

time taken for the briquette to burn was noted. The burning rate of the briquette was calculated using Equation (2.7).

$$Burning\ rate = \frac{Mass\ of\ burnt\ briquette}{Time\ taken\ for\ briquette\ to\ burn} \quad (gmin^{-1}) \qquad (2.7)$$

2.6.2 Ignition Time

This is the time taken for a briquette to ignite. Each briquette was lit using a gas flame. The time taken for each sample to ignite until it was self-sustaining to burn without any external flame was recorded as the ignition time using a stopwatch.

2.6.3 Proximate Analysis

2.6.3.1 Percentage Volatile Matter

This was determined by ASTM (2013). 50 grams of briquettes were dried in an oven at 105℃ for one hour and later heated in the furnace at 550℃ for 10 minutes. The residue was reweighed after cooling, and the percentage volatile matter was determined using Equation (2.8)

$$\%VM = \frac{X - Y}{G} \times 100 \quad (\%) \qquad (2.8)$$

Where:

$G = initial\ weight\ of\ the\ sample, g;$
$X = weight\ of\ dry\ matter, g$
$Y = weight\ of\ residue, g$

2.6.3.2 Ash Content

The amount of incombustible material remaining after burning the briquette sample (Ohagwu et al., 2022) was determined by ASTM (2013) as percentage ash content (%ash) using Equation (2.9). 50 grams of briquettes were heated in the furnace at 550℃ for 4 hours, and the residue was reweighed after cooling.

$$\%ash = (S/G) \times 100 \quad (\%) \qquad (2.9)$$

Where: $S = weight\ of\ ash\ residue, g.$

2.6.3.3 Moisture Content

Based on ASTM (2013), 50 grams of briquettes were heated in an oven at 105℃ for one hour, and the percentage moisture content (%MC) was calculated using Equation (2.10).

$$\%MC = \frac{G - X}{G} \times 100 \quad (\%) \qquad (2.10)$$

2.6.3.4 Percentage Fixed Carbon (%FC)

The solid combustible residue that remains after expelling the volatile matter from the briquette was calculated using Equation (2.11)

$$\%FC = 100 - (\%VM + \%ash + \%MC) \quad (\%) \qquad (2.11)$$

2.6.3 Heating Value (HV)

This is the heat produced by the complete combustion of a unit quantity of the briquette. The heating value (H_v) was calculated using the Gouthal formula, Equation (2.12)

H_v = 2.326 (147.6C + 144V). (2.12)

Where, H_v is the heating value in ($KJKg^{-1}$), C is the percentage of fixed carbon, and V is the percentage of volatile matter (Baileys et al., 1982). However, the values were converted to MJ/kg by dividing each value by 1000.

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

2.6.4 Elemental Analysis

The importance of proximate analysis is to determine the elemental composition of the briquettes. For energy materials, the three common critical elements are Carbon (C), Hydrogen (H), and Oxygen (O). According to Parikh et al. (2007), The biomass elemental compositions, Carbon (C), Hydrogen (H), and Oxygen (O) at 95% confidence interval were estimated using Equations (2.13), (2.14), and (2.15), respectively.

$$C = 0.637F_c + 0.455V_m \quad (2.13)$$

$$H = 0.052F_c + 0.062V_m \quad (2.14)$$

$$O = 0.304F_c + 0.476V_m \quad (2.15)$$

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

2.7 Data Analysis

Statistical Package for Social Sciences (SPSS, Version 16.0) software was used for descriptive statistics analysis, mean separation with Tukey's multiple comparison test at 5% significant level using Complete Randomized Design (CRD); MATLAB 2015a for data visualization.

2.8 Limitation

The heating values were calculated using the Gouthal formula from the proximate analysis rather than measured by bomb calorimetry.

3 RESULTS AND DISCUSSION

3.1 Combustion Properties

3.1.1 Proximate Analysis, Burning Rate, and Ignition Time

The proximate analysis, burning rate, and ignition time results obtained in this study are presented in **Table 1.**

Table 1: proximate analysis, burning rate, and ignition time

Binder (%)	%Volatile matter (%)	%Ash content (%)	%Moisture content (%)	%Fixed Carbon (%)	Heating Value (HHV) (MJ/kg)	Burning rate (g/min)	Ignition time (min)
Starch							
5	66.60±0.02[a]	7.56±0.00[a]	14.73±0.01[a]	11.03±0.03[a]	26.09±0.01[a]	0.18±0.01[a]	1.67±0.01[a]
15	66.75±0.01[b]	7.16±0.00[b]	15.19±0.01[b]	10.90±0.02[a]	26.10±0.00[a]	0.22±0.01[b]	1.72±0.01[b]
25	70.84±0.01[c]	6.12±0.01[c]	11.88±0.01[c]	11.16±0.03[b]	27.56±0.01[b]	0.25±0.00[c]	1.77±0.00[c]
35	74.84±0.01[d]	6.31±0.01[d]	7.86±0.01[d]	11.00±0.04[a]	28.84±0.01[c]	0.37±0.00[d]	1.78±0.00[d]
Okra							
5	73.00±0.01[e]	8.81±0.01[e]	6.64±0.01[e]	11.55±0.02[c]	28.42±0.00[d]	0.13±0.01[e]	1.67±0.01[e]
15	73.48±0.01[f]	9.02±0.01[f]	6.48±0.01[f]	11.02±0.03[a]	28.39±0.01[d]	0.14±0.00[e]	1.68±0.01[e]
25	76.58±0.01[g]	9.72±0.01[g]	3.57±0.01[g]	10.13±0.03[d]	29.13±0.01[e]	0.15±0.00[e]	1.71±0.00[f]
35	70.56±0.01[h]	8.18±0.01[h]	10.05±0.02[h]	11.21±0.03[b]	27.48±0.01[f]	0.16±0.00[e]	1.71±0.00[f]

The tabulated values are means ± standard error of the three replicates. Values with the same superscript in each column are statistically the same using Tukey's HSD multiple comparisons test at 5% significance level

The combustion characteristics of solid fuel are heavily dependent on its proximate and elemental compositions. Our findings demonstrated the significant influence of binder types and concentrations on these properties.

3.1.1.1 Volatile Matter (VM) and Fixed Carbon (FC)

Volatile matter is essential for both ignition and sustenance of flame. It ranged from 66.60% to 76.58% (**Table 1**). The okra-binder briquettes contained higher VM than their respective starch-binder briquettes. The highest VM, 76.58%, was revealed by 25% okra binder briquette. This could primarily be due to the complex carbohydrates and organic materials present in okra mucilage, which decompose at relatively lower temperatures. According to Ajimotokan et al. (2019), high VM contributes to better burning and sustained heat generation for domestic purposes, which the produced briquettes in this study exhibited. On the other hand, fixed carbon, essential for char burning and sustained heat generation, ranged from 10.13% to 11.55%. The findings revealed that briquettes containing high VM contents have low fixed carbon. **Figure 5** revealed the reliability of proximate analysis for determining volatile matter, as the findings had minimal standard error across all binder concentrations from 0.01% to 0.02%. However, fixed carbon showed a slightly significant variation across all binder concentrations due to somewhat higher standard errors from 0.02% to 0.04%. This could be due to the error made during the laboratory testing.

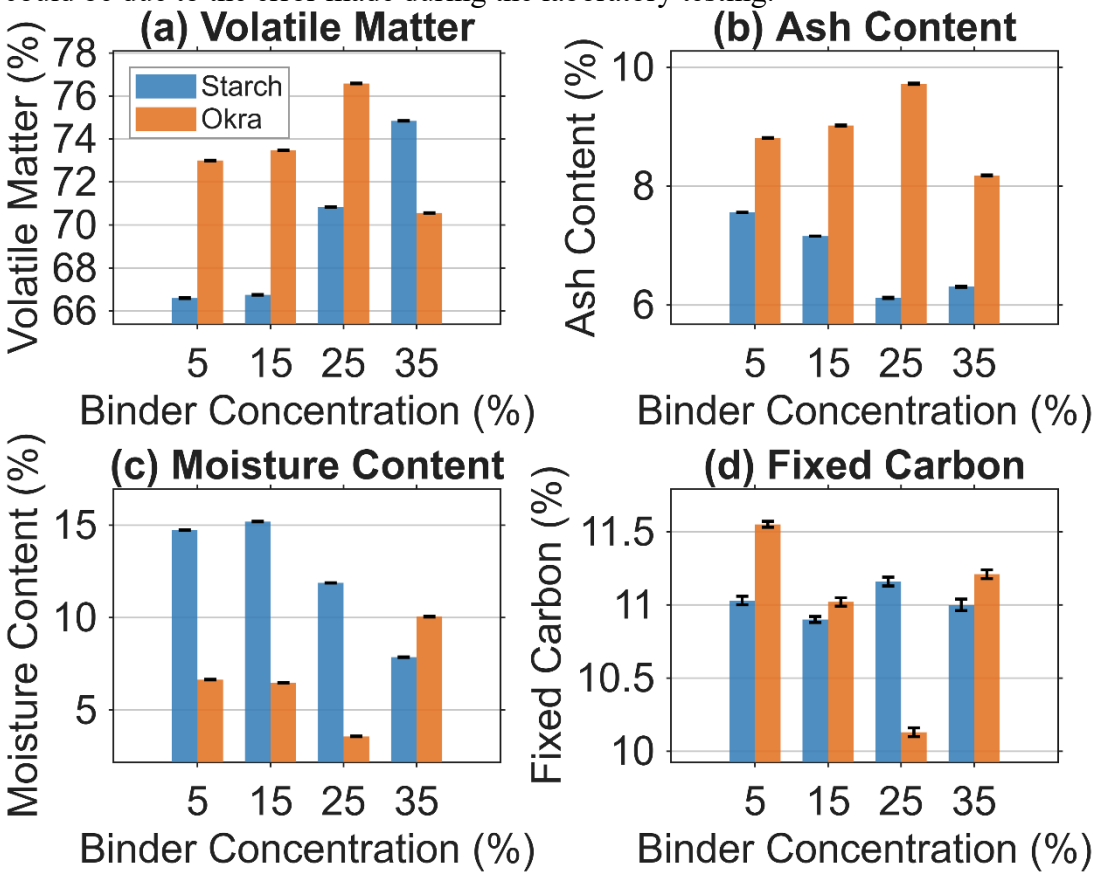


Figure 5: Effect of binder concentration on proximate analysis

3.1.1.2 Ash Content and Moisture Content (MC)

The ash content, a reflection of burning residue and slag formation, ranged from 6.12% to 9.72% (**Table 1)**. Findings revealed that okra-bound briquettes contain higher ash than starch-bound briquettes, reflecting higher innate contents in okra mucilage. Ash contents in this study slightly exceeded the European Standard for woody fuels (EN 14775) (<2%); however, it falls within the permissible thresholds for agricultural by-crops. The 25% starch-briquette sample with the lowest ash content of 6.12% would form very little slag. Another important parameter for burning efficiency and safe storage is MC. Okra-bound briquettes exhibited distinctly lower MC of 3.57%-10.05% than their respective starch-bound briquettes of 7.86%-15.19%. The 25% okra sample possessed the lowest MC of 3.57%. This underscores okra's superior properties for briquette preparation and draining, well within the desirable threshold for top-class briquette (<10%) described in EN 14961-1 standards (Hahn, 2004). Low MC directly reveals high net calorific value and clean-burning rates. **Figure 5** clearly shows the consistency and less variability in the measured moisture and ash contents in this study, owing to minimal standard errors recorded. This implies that the analytical methods used can be reproducible

3.1.1.3 Heating Value (HV)

The heating value (HV) is always considered the definitive measure of fuel energy value. The HV of briquettes in this study, 26.09 MJ/kg-29.13 MJ/kg, not only exceeded the minimum requirement in Europe at 16.50 MJ/kg but also outperformed that of pineapple peels at 25.08 MJ/kg (Mibulo et al., 2023), firewood (∼16 MJ/kg) and almost reached that of charcoal (∼29.5 MJ/kg) (Islam et al., 2014). It was observed that the 25% okra briquette possessed the highest HV of 29.13 MJ/kg. This directly arose from its well-optimized highest VM content of 76.58% and the lowest MC content of 3.57%, both of which are vital for enhancing energy density using the Gouthal formula. This result is crucial, placing pineapple leaf-okra briquettes as an energy-rich alternative to common solid fuels. **Figure 6** shows the non-linear variation of the heating values across all binder concentrations. However, for the starch binder, there was linearity from 15% to 35% binder concentrations. This revealed that increasing starch concentration from 15% increases the heating value of the briquettes. The errors recorded were very small, ranging from 0.00% to 0.01%. This further revealed that the heating value exhibited minimal variability across all binder concentrations, which means that the Gouthal formula used in this study was reliable and excellent for reproducibility.

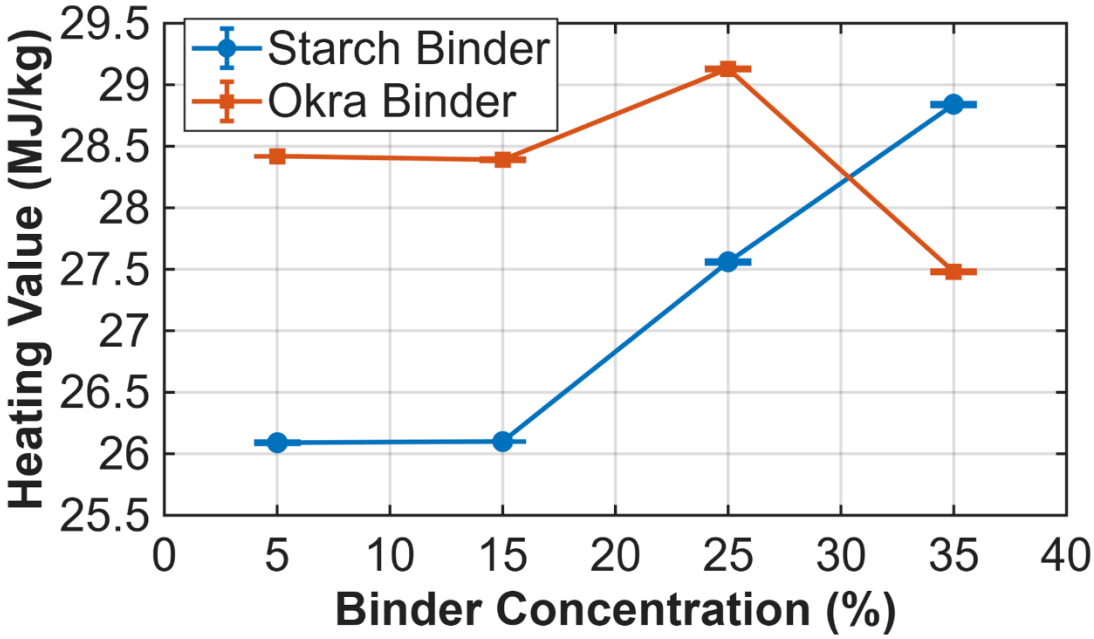


Figure 6: Effect of binder type and concentration on the heating value of briquettes

3.1.1.4 Burning Properties

The burning rates ranged from 0.13 g/min to 0.37 g/min, and ignition time from 1.67 min to 1.78 min, which are additional parameters that proved the fuel quality; however, they didn't correlate with the heating value and were dependent on the binder concentrations. The slower burning rates of okra briquette fuels (0.13-0.16 g/min) than starch briquette fuels revealed that okra briquette fuels burn for a longer period, which is desirable for cooking and heating. The ignition times for all produced briquettes were substantially shorter than for other biomass briquette fuels reported in previous studies (3-15.33) mins (Onukak et al., 2017; Zakka et al., 2024), indicating a very good ignitability of the produced briquettes in this study, which is one important user-friendly characteristic.

3.1.2 Elemental Analysis: The Molecular Basis of Combustion

The results of the elemental analysis: Carbon (C), Hydrogen (H), and Oxygen (O) contents of the briquettes were presented in **Table 2**.

Table 2: Carbon, hydrogen, and oxygen composition of the produced briquette samples

Binder (%)	C (%wt.)	H (%wt.)	O (%wt.)
Starch			
5	37.33±0.01^{a}	4.70±0.00^{a}	35.05±0.00^{a}
15	37.31±0.01^{a}	4.71±0.00^{a}	35.09±0.00^{b}
25	39.34±0.01^{b}	4.97±0.00^{b}	37.11±0.00^{c}
35	41.06±0.02^{c}	5.21±0.00^{c}	38.97±0.01^{d}
Okra			
5	40.57±0.01^{d}	5.13±0.00^{e}	38.26±0.00^{e}
15	40.45±0.02^{e}	5.13±0.00^{e}	38.33±0.01^{f}
25	41.30±0.02^{f}	5.27±0.00^{f}	39.53±0.00^{g}
35	39.25±0.02^{g}	4.96±0.00^{g}	37.00±0.01^{h}

C=Carbon, H=Hydrogen, O=Oxygen

The tabulated values are means ± standard error of the three replicates. Values with the same superscript in each column are statistically the same using Tukey's HSD multiple comparisons test at 5% significance level.

The data obtained from elemental analysis (**Table 2**) provides primary information about fuel energy content. The primary energy, contributing element in this study, carbon, varied between 37.31% and 41.30%. The 25% okra briquette showed the highest carbon content of 41.30%, indicative of its highest HV. Hydrogen, second to carbon in terms of its heat of combustion (Nhuchhen et al., 2017), also exhibited its highest content of 5.27% at 25% okra briquette. Oxygen, though very important for combustion, above certain percentages can reduce fuel energy content, since it marks oxidation formation already present in fuels. Oxygen content in this study varied between 35.05% and 39.53%, well within standards for fuel energy content for biomass, recommended as (30%-45%) (Zinla et al., 2021). The 25% okra briquettes achieved the highest carbon, hydrogen, and oxygen contents within the recommended range: (30%-60%) for carbon, (5%-6%) for hydrogen, and (30%-45%) for oxygen, which do not reduce their fuel energy content (Zinla et al., 2021). This is clearly shown in **Figure 7,** where the peak values of carbon, oxygen, and hydrogen are all at 25% binder concentration. At each binder concentration, the variability in the elemental composition was minimal, with a small standard error ranging from 0.00% to 0.02%. This reveals the outstanding reliability of the analytical method and uniformity of briquettes' compositions. Therefore, it supports the claim that the empirical formula, the Parikh formula, can be reliable for determining a briquette's elemental composition with better precision.

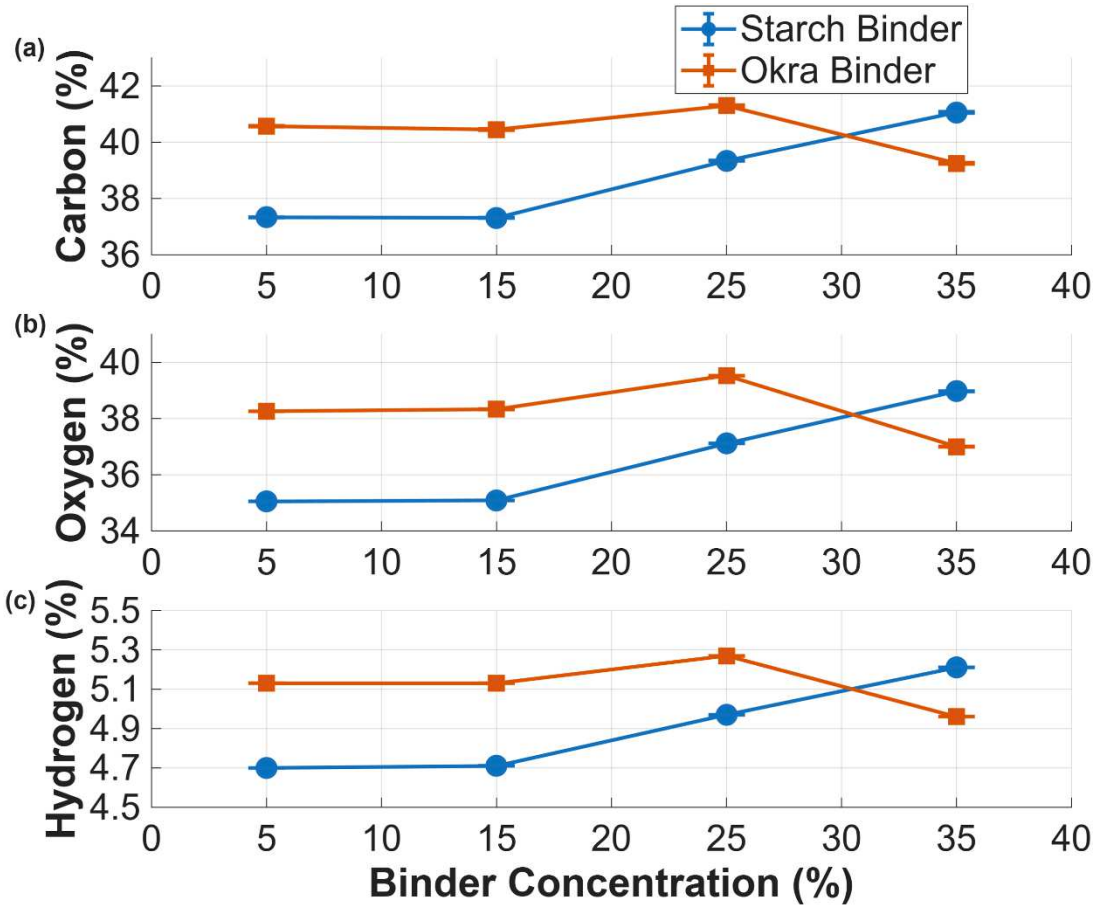


Figure 7: Effect of binder concentration on carbon, hydrogen, and oxygen compositions of briquettes

3.2 Mechanical Properties: Ensuring Durability for Handling and Transport

Table 3: Effect of binder ratio on density of briquettes

Binder ratio (%)	Density using okra binder (kg/m^3)	Density using starch binder (kg/m^3)
5	592.18 ± 0.08^{b}	664.07 ± 0.05^{b}
15	581.63 ± 0.19^{c}	717.42 ± 0.29^{c}
25	664.96 ± 0.00^{d}	728.91 ± 0.34^{d}
35	616.01 ± 0.12^{e}	750.14 ± 0.03^{e}

The tabulated values are means ± standard error of the three replicates. Values with the same superscript in each column are statistically the same using Tukey's HSD multiple comparisons test at 5% significance level.

Table 4: Effect of binder ratio on shatter resistance

Binder ratio (%)	Shatter resistance using okra binder (%)	Shatter resistance using starch binder (%)
5	96.74 ± 0.07^{a}	97.14 ± 0.00^{a}
15	99.96 ± 0.03^{b}	96.01 ± 0.02^{b}
25	98.18 ± 0.00^{c}	97.54 ± 0.03^{a}
35	99.93 ± 0.04^{b}	99.96 ± 0.03^{c}

The tabulated values are means ± standard error of the three replicates. Values with the same superscript in each column are statistically the same using Tukey's HSD multiple comparisons test at 5% significance level.

Table 5: Effect of binder ratio on tumbling resistance

Binder ratio (%)	Tumbling resistance using okra binder (%)	Tumbling resistance using starch binder (%)
5	97.87 ± 0.00^{a}	96.16 ± 0.09^{a}
15	94.67 ± 0.05^{b}	96.30 ± 0.00^{a}
25	92.07 ± 0.01^{c}	99.62 ± 0.00^{b}
35	98.65 ± 0.00^{d}	96.00 ± 0.00^{a}

The tabulated values are means ± standard error of the three replicates. Values with the same superscript in each column are statistically the same using Tukey's HSD multiple comparisons test at 5% significance level.

Table 6: Effect of binder ratio on water resistance

Binder ratio (%)	Water resistance using okra binder (minutes)	Water resistance using starch binder (minutes)
5	1862.00 ± 0.00^{a}	1770.00 ± 0.00^{a}
15	1620.67 ± 0.67^{b}	1650.00 ± 0.00^{b}
25	1260.67 ± 0.67^{c}	1575.00 ± 0.00^{c}
35	1165.00 ± 0.00^{d}	1524.33 ± 0.33^{d}

The tabulated values are means ± standard error of the three replicates. Values with the same superscript in each column are statistically the same using Tukey's HSD multiple comparisons test at 5% significance level.

Table 7: Effect of binder ratio on compressive strength

Binder ratio (%)	Compressive strength (using okra binder) (KN/m^2)	Compressive strength (using starch binder) (KN/m^2)

5	8886.2±0.01[a]	7709.1±0.01[a]
15	7773.8±0.00[b]	8086.9±0.01[b]
25	7251.6±0.00[c]	7687.1±0.00[c]
35	8045.3±0.33[d]	7404.5±0.00[d]

The tabulated values are means ± standard error of the three replicates. Values with the same superscript in each column are statistically the same using Tukey's HSD multiple comparisons test at 5% significance level.

For solid fuels to gain market viability, they need to exhibit good mechanical strength to resist damage during handling and transport.

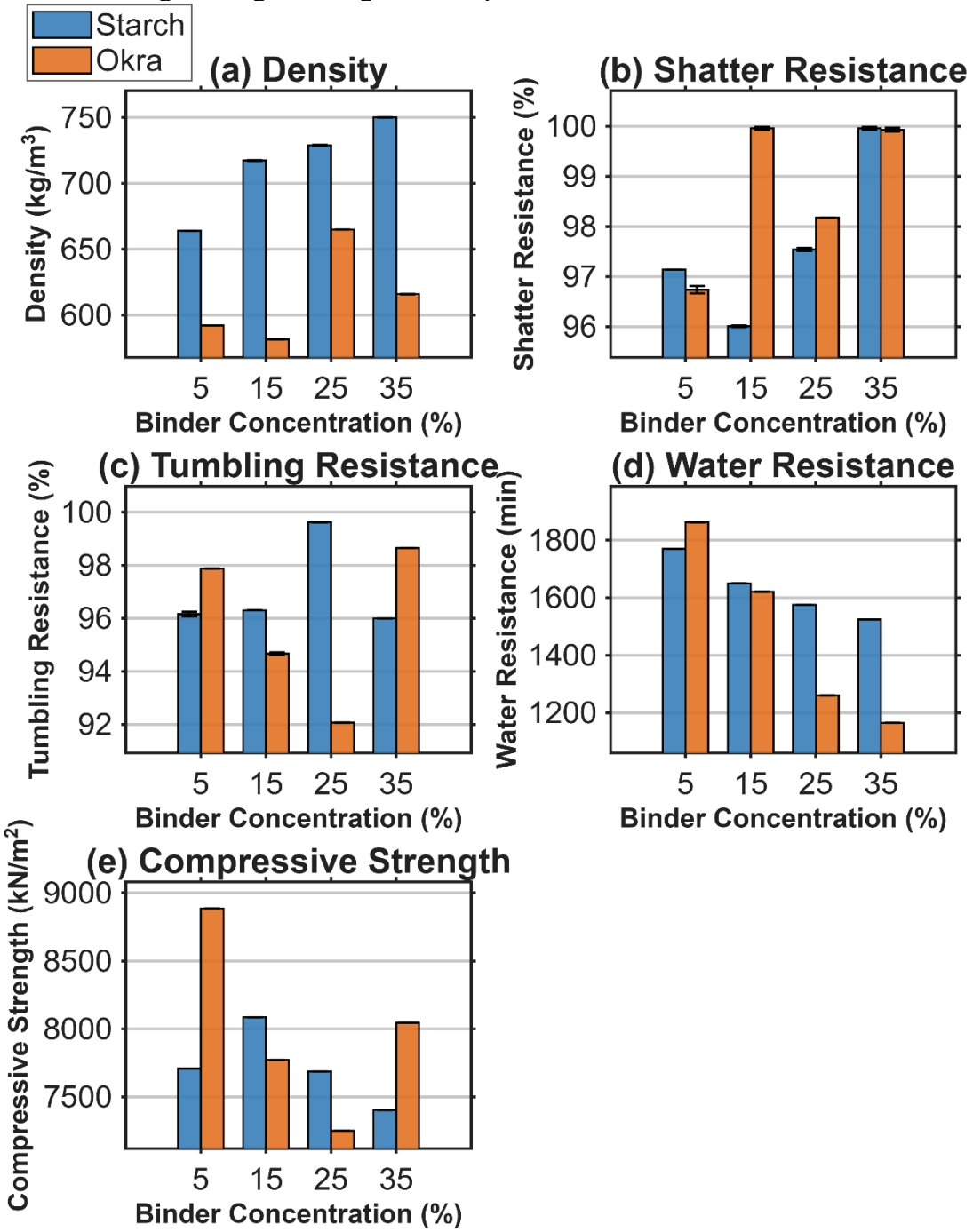


Figure 8: Effect of binder concentrations on the physico-mechanical properties

3.2.1 Density and Shatter Resistance

The densities of the produced briquettes ranged from 581.63 to 750.14 kg/m³ (T**able 3**), meeting the European standard requirement of ≥600 kg/m³ for most mixtures, except for 5% and 15% okra binder. They were higher than the 358.3–425.7 kg/m³ starch-bonded charcoal briquettes reported by Zubairu et al. (2014); and 530–580 kg/m³ reported by Jittabut, (2015) for rice straw and sugarcane leaves, but comparable to the 533-981 kg/m³ corn cob briquettes reported by Oladeji et al. (2012). Shatter resistance was excellent for all samples analyzed (96.01%-99.96%) (Table 4), exceeding the acceptable level of 80% reported by Adapa et al. (2003) and Tabil et al. (1996) The findings showed that the produced pineapple leaf briquettes were highly resistant to shattering or breaking during falls, making them safe for handling and transportation. **Figure 8 (a) and (b)** revealed minimal standard errors recorded from the analysis for both density and shatter resistance (0.00% - 0.34%). This implies that the methods used to determine density and shatter resistance were generally reliable and reproducible.

3.2.2 Compressive Strength (CS)

The compressive strength (CS) (7251.6-8886.2 KN/m²) (**Table 7**) shows a critical, nonlinear correlation with binder concentration. The highest compressive strength was reported at 5% okra binder concentration (8886.2 KN/m²), followed by a general decline in strength for increasing binder concentration from 15% to 35%. Aransiola et al. (2019) observed that binder concentration significantly influences compressive strength. Therefore, below or beyond the optimum binder concentration, the binder tends to impart a "lubricating" action, with fewer points of contact between particles, sometimes generating "planes or voids" in the resulting matrix on evaporation, leading to reduced structural integrity. Starch binder briquettes also exhibited a similar pattern, wherein compression strength peaked at 15% binder concentration. However, according to Plistil et al. (2005), 1.969 KN/m^2 CS is considered sufficient to overcome handling disturbance. Therefore, all the briquettes from this study met the recommended standard. **Figure 8 (e)** shows that the method used to determine compressive strength was outstanding and reliable since the errors were very small (0.00% - 0.33%). It also shows minimal variability across all binder concentrations.

3.2.3 Water Resistance and Tumbling Resistance

The data obtained for water resistance was excellent. More than 18 hours or 1080+ minutes passed before the disintegration of all briquette samples (**Table 6**), making them "high quality" according to DIN 5173 standards, where only 20 minutes are expected for a high-quality briquette to disintegrate (Križan, 2007). High water resistance is very important for humid environments where briquettes are packed for storage. Tumbling resistance (**Table 5**), which shows how wearable they are, was also very good (>92.07% to 99.62%), meaning almost all were within ≥96.5% standard EN 14961-1 requirement, which ensures that briquettes are not destroyed during mass handling. **Figure 8 (c) and (d)** revealed excellent reliability and reproducibility of the analytical methods used to determine water resistance and tumbling resistance in this study. This was attributed to the minimal standard errors recorded.

4 CONCLUSION

Based on the findings revealed, pineapple leaves have high potential for use as a biomass material for briquette production. The produced briquettes revealed the following:

- The heating values at all binder ratios (26.09-29.13 MJ/kg) were all within the recommended value of the Briquette standard EN 14961-1 (≥16.50 MJ/kg). All proximate analysis tests, burning test, and elemental compositions were within the recommended standard.
- Physico-mechanical testing of the briquettes produced with varying concentrations of the binder material indicated satisfactory results within the recommended range. All the briquettes produced across different binder concentrations met the recommended range of compaction ratio, compressed density, relaxation ratio, shatter resistance, durability, water resistance, and compressive strength.
- In addition, the briquettes containing 25% okra binder material showed the best results. These briquettes exhibited the highest volatile matter (76.58%), elemental composition of carbon (41.30%), hydrogen (5.27%), and oxygen (39.53%), as well as the lowest moisture content (3.57%) and the highest heating value of 29.13 MJ/kg. 25% okra-bound briquettes met all the required physico-mechanical standards of high-quality briquettes.

Further research should be carried out on the influence of particle size and pressure on pineapple leaf briquettes, on the performance of binder-less pineapple leaf briquettes, on the environmental and socio-economic impact assessment, and on the validation of the heating value using bomb calorimetry.

Credit Authorship Contribution

James Odur: Conceptualization, Methodology, Investigation, Laboratory work, Data curation, Formal analysis, Visualization, Writing – original draft, Writing – review and editing. **Onyekwere Ojike:** Supervision, Writing – review and editing. **Joel Nwaeze Nwakaire:** Supervision, Writing – review and editing.

Declarations

Ethics approval and consent to participate

Not applicable

Consent for Publication

Not applicable

Conflict of Interest

The authors declare that they have no conflict of interest.

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Data Availability Statement

The data presented in this study are all accessible in this article. Additional information may be requested from the corresponding author.

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Disclaimer

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