

Optimization of Binder Concentration and Particle Size for Elephant Grass and Sawdust Briquettes Using *Cissus Populnea* as Natural Binder



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ABSTRACT: The increasing demand for sustainable energy alternatives has renewed interest in the utilization of agricultural and forestry residues for solid biofuel production. In this study, elephant grass and sawdust were evaluated as feedstocks for briquette production using *Cissus populnea* (*okoho*) as a natural binder. Both biomass types, considered waste resources, were milled and sieved into four particle size fractions (1000, 500, 300, and 212 μm). Briquettes were produced with binder concentrations ranging from 0 to 35% and subsequently subjected to proximate analysis, density determination, and compressive strength, shatter resistance, tumbling resistance, and higher heating value tests. Response surface methodology was employed to generate predictive models, while ANOVA and regression analyses were used to assess factor significance. Results showed that binder concentration and particle size significantly influenced briquette quality parameters ($p < 0.05$), with higher binder levels and smaller particle sizes generally improving density and mechanical strength. Both feedstocks demonstrated good performance; however, sawdust briquettes exhibited superior overall properties, indicating their greater suitability for high-quality briquette production. These findings underscore the potential of locally available waste biomass and natural binders in the development of renewable energy solutions.

Keywords: Briquettes, *Cissus populnea*, Elephant grass, Sawdust, Waste biomass

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I. INTRODUCTION

Biomass briquettes have emerged as a sustainable alternative to conventional fossil fuels due to their renewable nature and ability to address environmental concerns associated with energy production (Geberehiet et al., 2025a; Nonsawang et al., 2024). These briquettes, produced from organic materials such as elephant grass and sawdust, offer a promising solution for sustainable energy generation. The use of agricultural residues for briquette production not only mitigates waste management challenges but also reduces environmental degradation linked to fossil fuel consumption. (Dinesha et al., 2019).

Biomass briquetting is an efficient and storable method for converting biomass residues into a compact, high-energy-density fuel with minimal heating costs. (Ohagwu et al., 2022) highlighted the potential of biomass briquettes as an alternative energy source, particularly considering the vast quantities of biomass waste generated by forestry and agricultural operations. The densification process enhances the energy potential of biomass, producing a homogeneous solid fuel with improved combustion characteristics (Marreiro et al., 2021). Furthermore, biomass briquettes contribute to clean energy production, reducing greenhouse gas emissions and improving indoor air quality, particularly in household applications (Nonsawang et al., 2024).

Elephant grass (*Pennisetum purpureum*) and sawdust are widely available agricultural and industrial by-products, respectively with significant potential for briquette production (Marafon et al., 2020). Elephant grass, a fast-growing perennial species, is widely cultivated as a sustainable biomass feedstock. At the same time, sawdust, a by-product of the wood processing industry, is both abundant and cost-effective. Studies suggest that elephant grass biomass briquettes exhibit desirable properties such as high compressive strength and low ash residue, enhancing combustion efficiency and reducing environmental impact (Boateng et al., 2025).

Cissus populnea (locally known as *Okoho*) is a perennial climbing plant of the Vitaceae family widely utilized in West Africa for both food and medicinal purposes (Rotimi et al., 2023). The stem bark of the plant is highly valued because it releases a gummy mucilage when soaked in water, giving it a viscous texture that is traditionally used as a thickener in soups. This gummy property makes it particularly suitable as a natural binder in food and industrial applications, including biomass briquetting. Importantly, *C. populnea* is a wild-sourced plant, and the use of its stem bark as a binder does not compete with conventional food resources since it is not cultivated as a staple crop but instead harvested from natural vegetation. Beyond its rheological potential, *C. populnea* is also recognized for its bioactive compounds, including saponins, flavonoids, and polysaccharides, which contribute to its functional properties.

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Its ready availability and natural adhesive qualities have attracted research interest as a sustainable alternative to synthetic binders (Alakali et al., 2009; Mark et al., 2018).

The biomass briquetting process involves compressing loose biomass materials into dense, compacted units known as briquettes (Obi et al., 2022). This process increases the energy density of biomass, simplifying handling, transportation, and storage. Biomass briquettes are used in diverse applications, including domestic heating, industrial energy use, and electricity generation. Sawdust, in particular, is an ideal material for biomass briquetting due to its high availability, cost-effectiveness, and renewable characteristics (Adegoke et al., 2022). Research has highlighted the suitability of sawdust in fabricating high-quality biomass briquettes, making it a viable choice for sustainable energy generation (Batool et al., 2021). Additionally, sawdust possesses natural binding properties that enable the formation of durable briquettes without synthetic binders (Sotande et al., 2010). The high calorific value of sawdust makes it an efficient fuel source (Antwi-Boasiako and Acheampong, 2016). The reduced moisture content in sawdust enhances combustion efficiency and consistency (Saeed et al., 2021). Sawdust briquettes serve as a commendable substitute for conventional fuels in heating applications within residential and industrial settings (Lela et al., 2016). Moreover, utilizing sawdust for biomass briquetting reduces carbon emissions compared to fossil fuels, contributing to climate change mitigation (Liu et al., 2018).

A key factor affecting the quality and performance of biomass briquettes is the particle size of the raw materials (Marreiro et al., 2021). The impact of particle size on briquette quality depends on factors such as biomass composition and compaction pressure (Gendek et al., 2018; Obi et al., 2022). Variations in particle size significantly influence briquette properties, including density, porosity, compressibility, calorific value, and combustion characteristics (Ohagwu et al., 2022). Understanding these effects is crucial for optimizing the briquetting process and improving the efficiency of biomass briquettes. Temperature also plays a critical role in biomass pyrolysis, affecting product composition and yield. Lower temperatures favour char formation, while higher temperatures result in greater gas and liquid production (Demirbas and Demirbas, 2007; Emami Taba et al., 2012). Studies indicate that additives such as charcoal and bentonite can enhance combustion efficiency while reducing emissions (Falemara et al., 2018). Another critical parameter is briquette thermal stability, which is defined as resistance to high temperatures without degradation (Zhang et al., 2018).

Although the significance of particle size has been recognized, systematic studies examining its effects on biomass briquettes, particularly those made from sawdust and elephant grass, remain limited. Research on different elephant grass species, chemical composition, and calorific value by (Marafon et al., 2020) emphasizes its feasibility for energy production. In addition, some researchers have explored the use of elephant grass processing derivatives, such as broth and bagasse, for energy generation, further underscoring the versatility of the biomass as a renewable energy resource (da Silva et al., 2025). Therefore, further comprehensive research is needed to clarify how particle size variations influence the

quality and functionality of these briquettes (Fruhstorfer and Aneziris, 2017; Houghton et al., 2024). This study aims to investigate the effect of binder concentration and particle size on the physico-mechanical and fuel properties of sawdust and elephant grass briquettes utilizing *Cissus populnea* (*oko*ho) as a binder. The research seeks to enhance biomass briquette production for improved energy efficiency, mechanical integrity, and environmental sustainability.

II. MATERIALS AND METHOD

Elephant grass (*Pennisetum purpureum*), sawdust, and *Cissus populnea* (*Okoho*) were the major raw materials used in this study. Elephant grass, a fast-growing perennial grass, was selected as a representative lignocellulosic biomass due to its abundance, high fiber content, and established use as an energy crop (Jenkins et al., 1998). Sawdust, a common by-product of wood processing, was incorporated as a supplementary biomass material, taking advantage of its fine particle size and wide availability as a low-cost waste resource. *Cissus populnea* stem bark was obtained from the wild and utilized as a natural binder because of its characteristic gummy mucilage, which provides strong adhesive properties when mixed with water (Mark et al., 2018). The choice of these materials was informed by their local availability, low cost, and potential for sustainable utilization in briquette production.

A. Materials

1) Elephant grass

Fresh elephant grass was sourced from the Department of Agricultural and Bioresources Engineering, University of Nigeria, Nsukka. The harvested biomass was sun-dried to reduce its moisture content, after which it was chopped into smaller pieces and ground into finer particles. This preprocessing step is essential to achieving the optimum particle size required for effective densification during briquetting. Proper size reduction improves binding, enhances compaction, and ultimately contributes to the production of strong, durable briquettes.

2) Sawdust

Sawdust, a by-product of wood processing, was sourced from the Timber Shade Nsukka sawmill. The biomass was air-dried to reduce excess moisture and subsequently ground to obtain a finer particle size suitable for briquetting. Incorporating sawdust in briquette production not only enhances compaction and combustion efficiency but also contributes to sustainable waste management and energy recovery from industrial residues.

3) *Cissus populnea* (*oko*ho) as a binder

Cissus populnea, locally known as *oko*ho, was employed as a natural binder to improve the cohesion and durability of the briquettes. The stem bark was harvested, thoroughly washed to remove dirt, and sun-dried to reduce its moisture content. It was then ground into a fine powder using a locally available attrition mill and stored in airtight containers to prevent moisture absorption and degradation. The binding property of *oko*ho ensures better particle adhesion during compaction, resulting in briquettes with greater mechanical strength and stability. The choice of *oko*ho over synthetic

binders such as starch, clay, or gum arabic is due to its local availability, affordability, and non-toxic nature (Adebowale et al., 2013). Additionally, it enhances the environmental sustainability of the briquetting process by replacing chemical additives with a renewable, biodegradable alternative. Figure 1 shows the image of the raw materials used for the briquette production.



Figure 1 Sawdust (A), Elephant grass (B), *Cissus populnea* (okoho) (C), weighed samples before briquette production (D)

B. Briquette production

Elephant grass was harvested, sun-dried, and ground into fine particles suitable for briquetting. Sawdust obtained from mahogany wood was also dried and ground to ensure uniform particle size distribution. Particle size analysis was performed using sieves of 1000 μm , 500 μm , 300 μm , and 212 μm mesh sizes mounted on a digital sieve shaker (Haver and Boeker, Germany; Serial No. 59302 OELDE). For each experimental batch, a total of 300 g of biomass was weighed and moistened with 50 mL of water to achieve the required binding consistency. The biomass was then blended with *Cissus populnea* (Okoho) at binder concentrations ranging from 0% to 35% of the biomass weight, in increments of 5%. Thorough mixing was carried out to ensure homogeneous distribution of the binder within the biomass matrix. The resulting mixtures were compacted into briquettes using a manual hydraulic press, after which the briquettes were air-dried under ambient conditions for seven days prior to analysis.

1) Experimental Setup

For each particle size of the biomass (elephant grass and sawdust) and each binder concentration of *Cissus populnea* (okoho), briquette production was replicated three times to ensure accuracy and reproducibility. The binder concentrations were designated as A, B, C ... H, corresponding to 0%, 5%, 10%, 15%, 20%, 25%, 30%, and 35% of the biomass weight, respectively. Similarly, the particle sizes were designated as 1, 2, 3, and 4, corresponding to 1000 μm , 500 μm , 300 μm , and 212 μm , respectively.

This factorial arrangement yielded 32 experimental conditions (8 binder concentrations \times 4 particle sizes). Each condition was replicated three times, giving a total of 96 experimental runs for subsequent analysis.

C. Methods

1) Equipment and their functions

A digital weighing balance was employed to ensure precise measurement of biomass and binder samples, thereby maintaining accurate mixing ratios essential for reproducibility (Oladeji, 2015). A sieve shaker (Haver & Boeker, Germany, Serial No. 59302) was used to perform particle size analysis through vibration-induced separation, ensuring uniform particle distribution, which directly enhances briquette density and combustion efficiency (Kujawiak et al., 2024). The dimensions of the briquette mould are 10cm by 10cm by 10cm. The hydraulic jack (20-ton screw jack) applied controlled pressure during compaction, enabling the formation of dense and durable briquettes (ASTM, 2006). To determine the moisture content of both biomass and briquettes, a laboratory oven (Model DGH-9101) was utilized, since moisture content significantly influences combustion performance, durability, and storage stability (ASTM, 2013).

A muffle furnace (Isotemp Model 186A, Fisher Scientific) was used for ashing, volatile matter determination, and high-temperature drying at up to 1000 $^{\circ}\text{C}$, providing data on the proximate composition of the briquettes (ASTM, 2007). After heating processes, desiccators were used to cool samples in a moisture-free environment, thereby preventing the reabsorption of water that could compromise test results (Onuegbu et al., 2011). A meter rule was used to measure briquette dimensions, such as length, breath and height., ensuring uniformity and enabling accurate density calculations (Oladeji, 2012). In addition, a twin-column universal material testing machine (M500-25CT) was employed to assess the compressive strength of the briquettes, providing a reliable measure of their mechanical durability during storage and transportation (Yaman et al., 2001). Figure 2 shows the hydraulic briquetting machine and the produced briquettes.

D. Proximate Analysis of Briquettes

Proximate analysis of the briquettes was carried out to determine their moisture content, volatile matter, ash content, and fixed carbon following standard ASTM procedures.

1) Moisture content

Approximately 2 g of each briquette sample was oven-dried at 105 ± 5 $^{\circ}\text{C}$ in a laboratory drying oven until a constant weight was obtained. The percentage moisture was calculated as the weight loss relative to the initial mass using equation (1).

$$MC(db) = \frac{W_i - W_f}{W_i} \times 100 \quad (1)$$

where

$MC(db)$ = Moisture content (dry basis) (%)

W_i = Initial weight of sample (g)

W_f = Final weight of sample (g)

2) Volatile matter

The oven-dried sample was placed in a covered crucible and heated in a muffle furnace at 950 ± 20 $^{\circ}\text{C}$ for 7 minutes. The percentage volatile matter was determined as the weight loss after heating, excluding moisture as seen in equation (2)

$$\text{Volatile matter (\%)} = \frac{\text{Weight Loss After Heating}}{\text{Dried Sample Weigh}} \times 100 \quad (2)$$

3) Ash content

A weighed sample was placed in a porcelain crucible and combusted in the muffle furnace at 750 ± 25 °C for 2 hours until a constant weight was achieved. Equation (3) shows the residue remaining expressed as the ash percentage.

$$\text{Ash content (\%)} = \frac{\text{Residue weight}}{\text{Initial Sample Weight}} \times 100 \quad (3)$$

4) Fixed carbon

Fixed carbon content was determined by difference using the formula in equation (4).

$$\text{fixed carbon (\%)} = 100 - [\text{MC (\%)} + \text{VM (\%)} + \text{AC (\%)}] \quad (4)$$

where, *MC* is the moisture content, *VM* is volatile matter and *AC* is ash content. The results from proximate analysis were used to evaluate the fuel quality and combustion properties of the briquettes.

E. Determination of Physico-Mechanical Properties

The physico-mechanical properties of the briquettes were determined to assess their structural integrity, handling performance, and suitability for storage and transportation. The parameters evaluated included compressive strength, hardness, density, shatter resistance, tumbling resistance.

1) Compressive Strength

The compressive strength of the briquettes was determined using a Twin-Column Universal Material Testing Machine (M500-25CT) in accordance with ASTM D143-2008. Each briquette was subjected to an increasing axial load until fracture occurred. The compressive strength was calculated using Equation (5).

$$\text{Compressive strength (N/mm}^2\text{)} = \frac{\text{load at fracture (N)}}{\text{cross-sectional area (mm}^2\text{)}} \quad (5)$$

2) Density Determination

The density of the briquettes was determined using the mass-to-volume ratio method. The mass of each briquette was measured using a digital weighing balance, while dimensions (diameter and height) were measured with a meter rule to calculate the volume. Density was then obtained using Equation (6).

$$\text{Density (g/cm}^3\text{)} = \frac{\text{mass of briquette}}{\text{volume of briquette}} \quad (6)$$

3) Shatter Resistance Test

The shatter resistance of the briquettes was determined by dropping each briquette from a height of 1.85 m onto a hard concrete surface, following (ASTM 440, 2019) procedure. Each briquette was dropped four times, and the percentage weight retained after dropping was used as a measure of shatter resistance, as expressed in equation (7).

$$\text{Shatter resistance (\%)} = \frac{\text{weigh after dropping (g)}}{\text{initial weigh (g)}} \times 100 \quad (7)$$

4) Tumbling Resistance Test

Tumbling resistance was evaluated using a tumbling drum in line with (ASTM D441, 2021). A known weight of briquettes was placed in the drum and rotated at a constant speed (approximately 50 rpm for 4 minutes). After tumbling, the retained weight was measured, and the tumbling resistance was calculated using Equation (8).

$$\text{Tumbling resistance (\%)} = \frac{\text{weigh after tumbling (g)}}{\text{initial weigh (g)}} \times 100 \quad (8)$$

F. Determination of Thermal Properties using Higher Heating Value

The higher heating value (HHV) of the briquettes was estimated using the empirical correlation derived by, (Parikh et al., 2005) which relates heating value to proximate analysis results (fixed carbon, volatile matter, and ash content). The relationship is expressed in Equation (9):

$$\text{HHV} = 0.3536 \times \text{FC} + 0.1559 \times \text{VM} - 0.0078 \times \text{Ash} \quad (9)$$



Figure 2 (A) Briquetting process, (B) briquettes produced

G. Elemental properties of the briquettes

The elemental composition of the briquettes was estimated from proximate analysis results using established empirical correlations (Emami Taba et al., 2012; Marafon et al., 2020). The major elements considered were carbon (C), hydrogen (H), oxygen (O), and nitrogen (N). These parameters are essential in determining the fuel's combustion efficiency and emission characteristics. The relationships used are expressed in equations (10) to (13) with *FC* being the fixed carbon.

$$\%C = 0.637 \times \text{FC} + 0.445 \times \text{VM} \quad (10)$$

$$\%H = 0.052 \times \text{FC} + 0.062 \times \text{VM} \quad (11)$$

$$\%O = 0.304 \times \text{FC} + 0.476 \times \text{VM} \quad (12)$$

$$\%N = 100 - (\%C + \%H + \%O + \%ash) \quad (13)$$

II. RESULTS AND DISCUSSION

The results are presented in the following section

A. Proximate Analysis of Briquettes

The average proximate analysis for the different binder concentrations across the four particle sizes is presented in Tables 1 and 2.

Table 1 Proximate Analysis of elephant grass briquette

% BINDER	MC	VM	AC	FC
0	10.12	83.39	1.25	5.24
5	10.79	83.24	1.35	4.62
10	10.88	82.88	1.42	4.82
15	11.2	82.51	1.49	4.8
20	11.46	81.54	1.68	5.32
25	11.94	80.77	1.71	5.58
30	11.98	80.62	2.05	5.35
35	12.06	80.15	2.1	5.69

Table 2 Proximate Analysis of sawdust briquette

% BINDER	MC	VM	AC	FC
0	7.59	82.94	1.62	7.85
5	7.69	85.35	1.81	5.15
10	7.98	85.1	1.83	5.09
15	8.05	84.93	1.84	5.18
20	8.17	84.66	2.05	5.12
25	8.66	83.89	2.15	5.3
30	8.8	83.55	2.16	5.49
35	8.99	83.15	2.17	5.69

From the proximate analysis results presented in Tables 1 and 2, it is evident that the moisture content (MC) of both elephant grass and sawdust briquettes increased progressively with higher binder concentration, ranging from 10.12% to 12.06% for elephant grass and 7.59% to 8.99% for sawdust. Conversely, the volatile matter (VM) content generally decreased as the binder concentration increased, indicating improved stability of the briquettes with increasing binder addition. Ash content (AC) also increased slightly across the binder levels, while fixed carbon (FC) showed a marginal increase after 20–35% binder addition, suggesting enhanced carbon retention in the briquettes.

As shown in Table 3, the higher heating value (HHV) of the briquettes remained relatively stable across the binder concentrations, with elephant grass ranging between 14.44–14.84 MJ/kg and sawdust between 14.94–15.69 MJ/kg. This range is similar to what was obtained by other researchers for rice husk (Braga et al., 2014). This indicates that binder addition had only a minor effect on the energy content of the briquettes, with sawdust briquettes generally exhibiting higher HHV values compared to elephant grass.

Table 3 Heating values of elephant grass and sawdust briquettes

% BINDER	ELEPHANT GRASS HHV	SAWDUST HHV
0	14.84	15.69
5	14.60	15.11
10	14.61	15.05
15	14.55	15.06
20	14.58	14.99
25	14.55	14.94
30	14.44	14.95
35	14.49	14.96

B. Elemental composition of the briquettes

The elemental composition of the briquettes was determined to evaluate their fuel quality in terms of carbon, hydrogen, oxygen, and nitrogen contents. The results for elephant grass and sawdust briquettes at varying binder concentrations are presented in Tables 4 and 5.

Table 4 Elemental Composition of Elephant Grass Briquettes

% BINDER	C (%)	H (%)	O (%)	N (%)
0	40.4464	5.9430	41.2866	11.0740
5	39.9847	5.9006	41.0267	11.7380
10	39.9519	5.8865	40.9162	11.8254
15	39.7746	5.8603	40.7340	12.1412
20	39.6741	5.8214	40.4303	12.3942
25	39.4971	5.7825	40.1428	12.8675
30	39.2839	5.7604	40.0015	12.9043
35	39.2913	5.7461	39.8812	12.9815

Table 5 Elemental Composition of Sawdust Briquettes

% BINDER	C (%)	H (%)	O (%)	N (%)
0	41.9088	6.0481	41.8658	8.5573
5	41.2613	6.0716	42.1922	8.6649
10	41.1118	6.0515	42.0550	8.9517
15	41.0935	6.0446	42.0014	9.0205
20	40.9351	6.0231	41.8546	9.1371
25	40.7072	5.9801	41.5428	9.6199
30	40.6769	5.9669	41.4388	9.7575
35	40.6263	5.9501	41.3092	9.9445

The elemental analysis showed that carbon content decreased slightly with increasing binder concentration, from 40.45% to 39.29% for elephant grass and from 41.91% to 40.63% for sawdust. This trend was similar to what was obtained by Ohagwu *et al.* (Ohagwu et al., 2022). At the same time, nitrogen content increased, rising from 11.07% to 12.98% in elephant grass and from 8.56% to 9.94% in sawdust, indicating the binder introduced nitrogenous compounds. Hydrogen and oxygen remained relatively stable across binder levels with only minor variations.

Overall, sawdust briquettes exhibited higher carbon and lower nitrogen compared to elephant grass, suggesting better fuel quality and fewer NO_x emissions. The binder improved mechanical stability but slightly reduced energy content, highlighting the need for an optimum binder concentration to balance durability and fuel performance.

C. Comparison between the briquettes

To determine whether the observed differences between elephant grass and sawdust briquettes were statistically significant, a t-test was performed on their proximate, thermal, and elemental properties. The results are summarized in Table 6.

Table 6 T-Test Comparison of Elephant Grass and Sawdust Briquettes

VARIABLE	F-VALUE	SIGNIFICANCE (P<0.05)
MC	1.6771E-07	significant
VM	0.00123316	significant
AC	0.031883923	Not significant
FC	0.255502929	Not significant
HHV	0.000393067	significant
C	1.67715E-05	significant
H	6.47796E-05	significant
O	0.000104974	significant
N	1.53058E-07	significant

The findings reveal that significant differences existed in moisture content, volatile matter, higher heating value, and elemental composition (carbon, hydrogen, oxygen, and nitrogen) between the two feedstocks. In contrast, no significant differences were observed in ash content and fixed carbon, indicating that both materials exhibited similar behavior with respect to these two properties. Overall, sawdust briquettes demonstrated better fuel quality due to their higher carbon content and heating value, while elephant grass briquettes showed relatively higher nitrogen levels.

D. Physico-mechanical properties of elephant grass and sawdust briquettes

1) Moisture content of elephant grass and Sawdust briquettes

The response surface plot for moisture content is shown in Figure 3. Figure A and B present the response surface plots of moisture content as influenced by binder concentration and particle size for elephant grass and sawdust briquettes, respectively.

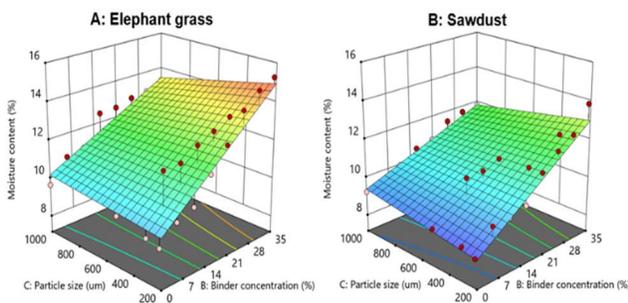


Figure 3 Response Surface Plots of Moisture Content (A) Elephant grass Briquettes and (B) sawdust briquette

For elephant grass, moisture content increased from 10 to 14% with higher binder concentrations and smaller particle sizes, showing a strong interaction between these two factors. The range obtained were similar to what was obtained by other researchers (Quaicoe et al., 2024). In sawdust briquettes, the effect of binder concentration was less pronounced, although smaller particle sizes still retained slightly more moisture than larger ones. Overall, both materials demonstrated that binder addition and particle size reduction tend to increase moisture

retention, with elephant grass showing greater variability compared to sawdust.

2) Effect of biomass on the density of briquettes samples

The response surface plots in Figure 4 illustrate the combined influence of binder concentration and particle size on the density of briquettes produced from elephant grass and sawdust. In both feedstocks, density was strongly dependent on binder concentration, with a marked increase observed as binder concentration rose from 0 to 35%. This finding highlights the critical role of binder in enhancing particle cohesion, reducing void spaces, and improving overall compaction during briquette formation.

Particle size also exhibited a significant effect, although its influence was less pronounced compared to binder concentration. Generally, smaller particle sizes (212–500 µm) yielded higher densities than larger particles (>800 µm), which can be attributed to better packing efficiency and reduced inter-particle voids. The interaction between the two variables revealed that maximum briquette densities were achieved when small particle sizes were combined with high binder concentrations, with densities approaching 650–700 kg/m³ for both feedstocks.

While elephant grass and sawdust showed similar overall trends, subtle differences were observed. The density response for sawdust appeared more sensitive to changes in binder concentration, suggesting that its finer natural structure may promote stronger binder-particle bonding. Conversely, elephant grass showed more variability across the particle size range, which may be related to its fibrous morphology and lower inherent bulk density. These differences underscore the importance of raw material characteristics in determining the compaction behavior and final quality of briquettes.

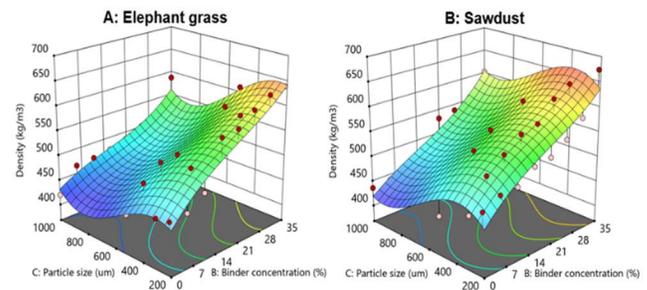


Figure 4 Response Surface Plots of Density of A: elephant grass briquettes B: sawdust briquettes

3) Compressive strength of the briquettes

Figure 5 illustrates the response surface plots showing the effect of binder concentration and particle size on the compressive strength of briquettes produced from elephant grass and sawdust. In both cases, compressive strength was predominantly influenced by binder concentration. As the binder concentration increased from 0 to 35%, compressive strength improved substantially, reaching values above 4 MPa. This behaviour is consistent with the role of binder in enhancing inter-particle bonding, thereby improving the load-bearing capacity of the briquettes (Obi et al., 2022).

Particle size also exerted a notable effect, with smaller particle sizes (212–409 µm) yielding higher compressive

strengths compared to coarser particles ($>800\ \mu\text{m}$). This trend can be explained by the higher packing density and greater surface area available for bonding in finer particles, which facilitates stronger structural integrity under applied loads. The combined effect of small particle size and high binder concentration resulted in the highest compressive strengths, demonstrating a clear interaction between the two factors.

Although the general patterns were similar for both feedstocks, differences were observed in the extent of response. Sawdust briquettes exhibited a more consistent and steeper increase in compressive strength with rising binder concentration, suggesting that their fine fibrous structure enhances binder effectiveness. Elephant grass, in contrast, showed more variability across the particle size range, likely due to its more coarse, fibrous morphology, which may limit particle interlocking and compaction efficiency.

Overall, the results suggest that binder concentration is the primary factor controlling briquette compressive strength, while particle size serves as a secondary important factor. The observed differences between elephant grass and sawdust further emphasize the role of feedstock characteristics in determining mechanical performance.

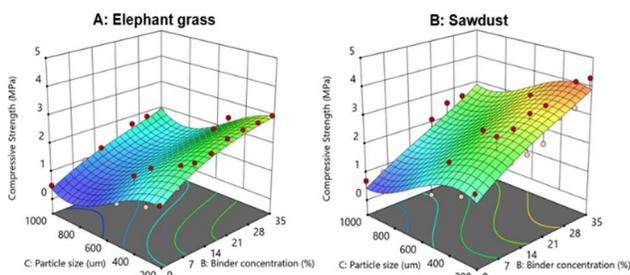


Figure 5 Response Surface Plots of Compressive strength of A: elephant grass briquettes B: sawdust briquettes.

4) Shatter resistance of the briquettes

The results from the response surface plots reveal pronounced effects of both binder concentration and particle size on the shatter resistance of briquettes produced from Elephant grass and Sawdust (Figure 6). For both materials, increasing either the binder concentration or the particle size consistently led to higher shatter resistance, indicating improved mechanical integrity and durability of the final briquette products.

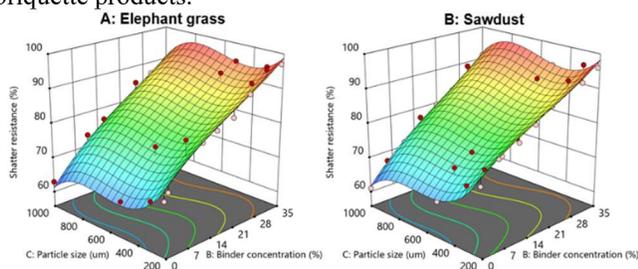


Figure 6 Response Surface Plots of Shatter resistance of A: elephant grass briquettes B: sawdust briquette

Binder concentration exhibited a strong positive correlation with shatter resistance across both substrates. The surfaces displayed marked increases in resistance as binder

percentage rose from 0% up to 35%. This trend underscores the critical role of binder in enhancing particle cohesion, reducing brittleness, and mitigating susceptibility to mechanical breakdown during handling and transportation. Notably, the response surface for Elephant grass showed a slightly steeper ascent, suggesting it may benefit more substantially from increased binder content compared to Sawdust. This may be attributable to the differences in intrinsic fiber composition and inter-particle adhesion properties between the two biomass sources.

Particle size also significantly influenced shatter resistance ($p < 0.05$). The increase in shatter resistance observed with decreasing particle size can be attributed to improved structural integrity of the briquettes. Finer particles enhance packing efficiency during compaction, resulting in higher briquette density and reduced internal porosity. This reduction in void spaces minimizes the presence of weak zones that could initiate crack formation during impact loading. (Geberehiet et al., 2025b). Additionally, smaller particles provide a larger specific surface area, which promotes stronger inter-particle bonding. Coarser particles tend to create non-uniform stress distributions due to larger voids and particle discontinuities, which act as stress-concentration points under impact. Both materials reached their highest resistance values at the $212\ \mu\text{m}$. The surface plot for Sawdust suggested a slightly more uniform response to particle size changes. In contrast, elephant grass appeared more sensitive to these variations, exhibiting a sharper gradient across the tested range.

5) Tumbling resistance of the briquettes

The response surface analyses clearly demonstrate that both binder concentration and particle size significantly affect the tumbling resistance of briquettes derived from Elephant grass and Sawdust (figure 7). Maximizing these two parameters leads to superior resistance against mechanical disintegration during handling, transportation, and storage—a crucial attribute for commercial viability of biomass briquettes.

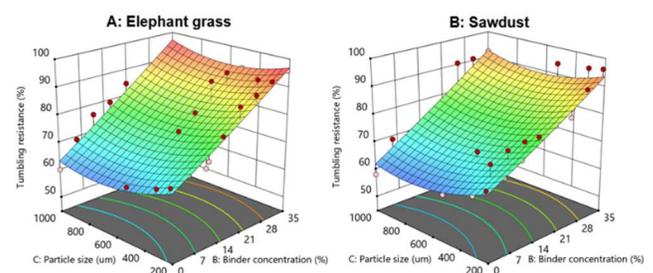


Figure 7 Response Surface Plots of Tumbling resistance of A: elephant grass briquettes B: sawdust briquettes

For Elephant grass, there is a pronounced sensitivity to these process variables. The steep ascent in the response surface indicates that even modest increases in binder or particle size can lead to significant improvements in tumbling resistance. This behaviour may stem from the fibrous nature and composition differences inherent to Elephant grass, which may require more binder for optimal particle interlocking and matrix formation.

Sawdust, on the other hand, exhibits a smoother, more predictable increase in tumbling resistance with increasing binder concentration and particle size. This trend implies that Sawdust-based briquettes may be less sensitive to abrupt parameter changes, offering more consistent performance across formulation adjustments. This property could make Sawdust an attractive feedstock for settings where process control and repeatability are critical.

Both substrates achieve comparable maximum tumbling resistance at the highest levels of binder and particle size, indicating that with optimal processing, either can yield robust briquettes suitable for diverse energy applications. These findings reinforce the necessity of careful raw material preparation and binder selection in bioenergy product development.

E. ANOVA and Regression Analysis

The data presented in Tables 7 and 8 includes the results from the Analysis of Variance (ANOVA) and Regression analysis, which are critical statistical methods for understanding relationships between variables. The table presents the statistical analysis of three key properties—Moisture Content (MC), Density, and Compressive Strength (CS)—for briquettes made from elephant grass and sawdust.

The effects of binder concentration (A), particle size (B), and their interaction (AB) were analyzed using regression models. The intercept values represent the predicted baseline for each property without the influence of the variables. The significance levels, indicated by asterisks (***) for $p < 0.001$, (**) for $p < 0.01$, and (*) for $p < 0.05$ effects, show the strength of the relationship between each factor and the briquette properties. The high R² values (ranging from 0.9 to 0.95) suggest that the models explain most of the variability in the data, indicating reliable predictive capability.

Examining the coefficients, binder concentration (A) has a consistently significant positive effect on all three properties for both materials, highlighting its importance in briquette formation. Particle size (B) significantly influences density and compressive strength, but has a negligible effect on moisture content. The interaction term (AB) shows minimal impact, with only a slight significance for moisture content. These results collectively provide insights into how material composition and processing parameters affect the physical and mechanical characteristics of the briquettes, forming a foundation for further optimization.

Table 7 Regression table for moisture content, density and compressive strength

	MC		Density		CS	
	Elephant grass	Sawdust	Elephant grass	Sawdust	Elephant grass	Sawdust
<i>Intercept</i>	9.55	8.368	369.214	332.459	8.178	3.213
<i>A: Binder concentration</i>	0.165***	0.142***	9.956***	8.95***	1.075***	1.125***
<i>B: Particle size</i>	0.001	0.001	0.709**	0.957**	0.063**	0.102**
<i>AB</i>	0.000071*	0.000071*	-0.006	-0.004	-0.0008	-0.0008
<i>R2</i>	0.9	0.9	0.92	0.92	0.95	0.95

Coefficients represent the effects of binder concentration (A), particle size (B), and their interaction (AB). Significance levels are indicated as: ***($p < 0.001$), **($p < 0.01$), *($p < 0.05$). R² values show the proportion of variance explained by the models.

Table 8: Regression analysis results for shatter resistance and tumbling resistance

	SR		TR	
	Elephant grass	Sawdust	Elephant grass	Sawdust
<i>Intercept</i>	117.24	126.27	74.639	74.534
<i>A: Binder concentration</i>	0.533***	0.374***	0.721***	0.636***
<i>B: Particle size</i>	-0.311***	-0.334***	-0.036*	-0.037*
<i>AB</i>	0.002**	0.002**	0.0002	0.0002
<i>R2</i>	0.94	0.94	0.91	0.91

V. CONCLUSION

This study evaluated the influence of binder concentration and particle size on the quality characteristics of briquettes produced from elephant grass and sawdust using *Cissus populnea* (okoho) as a natural binder. The experimental results, supported by ANOVA, regression analysis, and response surface methodology, revealed that both factors significantly affected briquette density, compressive strength, shatter resistance, tumbling resistance, and higher heating value. Increasing binder concentration and reducing particle size consistently enhanced briquette performance, leading to improved compaction, mechanical durability, and energy content. Both elephant grass and sawdust demonstrated promising potential as raw materials for briquette production. However, sawdust briquettes exhibited superior overall properties, particularly in terms of mechanical strength and energy value, highlighting their greater suitability for high-quality fuel applications. The use of *Cissus populnea* as a locally available natural binder further strengthens the sustainability of the process by reducing reliance on synthetic additives. Overall, this study underscores the viability of converting waste biomass into renewable energy carriers and provides a basis for optimizing briquette production parameters. Future research may focus on scale-up studies, long-term combustion performance, and economic feasibility to support the broader adoption of biomass briquettes as an alternative to conventional fuels.

AUTHOR CONTRIBUTIONS

E. I. Ugwu: Conceptualization, Methodology, Writing – original draft, Supervision, Writing – review & editing. N. N. Aneke: Validation, Software, Writing – review & editing. A. C. Okoro: Writing – review & editing, Validation. T. Ekemezie-Okoye: Writing – original draft, Methodology

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